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GEOLOGY OF THE URANIUM DEPOSITS OF THE LUKACHUKAI MOUNTAINS AREA, NORTHEASTERN ARIZONA

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ABSTRACT

A concentration of ore bodies occurs in a belt across the Lukachukai Mountains. The ore belt conforms to a facies of lenticular sandstone and mudstone that apparently provided sufficient permeable sandstone for the passage of ore solutions, and sufficient impermeable mudstone to restrict movement of solutions to particular sandstone beds. An unusual concentration of carbon appears to have served as a precipitation agent. Lateral changes in permeability of the sandstone beds, related to the old stream systems, influenced the movement of mineralizing solutions. The solutions apparently bleached red sandstones to gray or to limonitic brown.

Mapping of drill-core data shows that ore bodies (1) are elongate parallel to sedimentation, (2) tend to occur along the flanks of sandstone channels that are bounded laterally by zones of "flood-plain" lithology, (3) commonly occur in groups, (4) tend to "build up" against permeability barriers.

The degree of mineralization in an area is related to the initial quantity and quality of: (1) ore solutions, (2) carbon, and (3) permeability variations. Permeability changes probably do not directly cause precipitation, but are effective in the formation of large deposits.

INTRODUCTION

THE ideas advanced in this paper are a composite of personal conclusions and those acquired, through many discussions, from associates. To W. L. Stokes, University of Utah, belongs particular credit for his critical analysis of Salt Wash ore-controls and for instruction in mapping technique. L. J. Miller, J. D. Lowell, R. D. Blum, R. L. Rock, R. T. Zitting, and N. J. Clinton, all of the Atomic Energy Commission, participated in work of which this paper is one result.

GENERAL GEOLOGY

The Lukachukai Mountains are in the northeast corner of Arizona on the northeast flank of the Defiance uplift (Fig. 1).

About 3,000 feet of Paleozoic marine sediments underlie the Lukachukai Mountains (15). During Triassic and Jurassic time, the area was above sea level and received an additional 3,000 feet of fluviatile, lacustrine, and eolian sediments, which were deposited under environmental conditions ranging from tropic to arid. The Salt Wash sandstone member of the Morrison formation, upper Jurassic, was deposited as a large alluvial fan (5). This member is of primary interest because it carries most of the uranium deposits of the area. During Cretaceous time about 6,000 feet of marine and continental sediments were deposited (16). Following Laramide deformation all the Cretaceous and perhaps some early Tertiary rocks were eroded from the Lukachukai Mountains before deposition of the Chuska sandstone of Pliocene (?) age. The age of the Chuska is significant because of its bearing on the date of igneous activity in the region. D. L. Jones (personal communication) has identified fresh water ostracods of probable Pliocene age from the lower part of the Chuska.

STRUCTURAL AND IGNEOUS HISTORY

Laramide deformation of the Defiance uplift began in late Cretaceous and extended into the Eocene (11), resulting in the Defiance monocline and other structures (Fig. 1). In the vicinity of the Lukachukai Mountains, strike of the beds diverges from the north-trending monocline and swings around the northeast flank of the Defiance uplift. Doming around the Carrizo laccolithic intrusion was superimposed on these older structural trends.

The Lukachukai anticline, plunging northwest and sharply asymmetric, reverses by 10° to 30° the gentle (1½°) northeast dip off the Defiance uplift. This anticline, and the syncline that lies immediately to the south, are assumed to be Laramide in age. The anticline is a structure that is typical of the "monoclines" of the Colorado Plateau, characterized by abrupt change in dip, straight axis, and lack of secondary parallel folds. Baker (3) has suggested that such monoclines are related to deep-seated faults over which the surface rocks are draped. Such structures are possible loci of hydrothermal activity. Undoubtedly the structures influenced the rate and direction of Tertiary ground water movement, and the author believes that this is a factor of importance in ore deposition.

The Carrizo laccolith is the dominant structural and igneous feature in the area, and strata around the flanks of the intrusion dip as much as 25°. On the east and west sides of the laccolith, Jurassic rocks that strike west are cut by the intrusion (Fig. 2); hence it postdates Laramide deformation. This diorite-porphyry intrusion, and similar laccoliths of the Colorado Plateau, are believed to be Pliocene (?) (7).

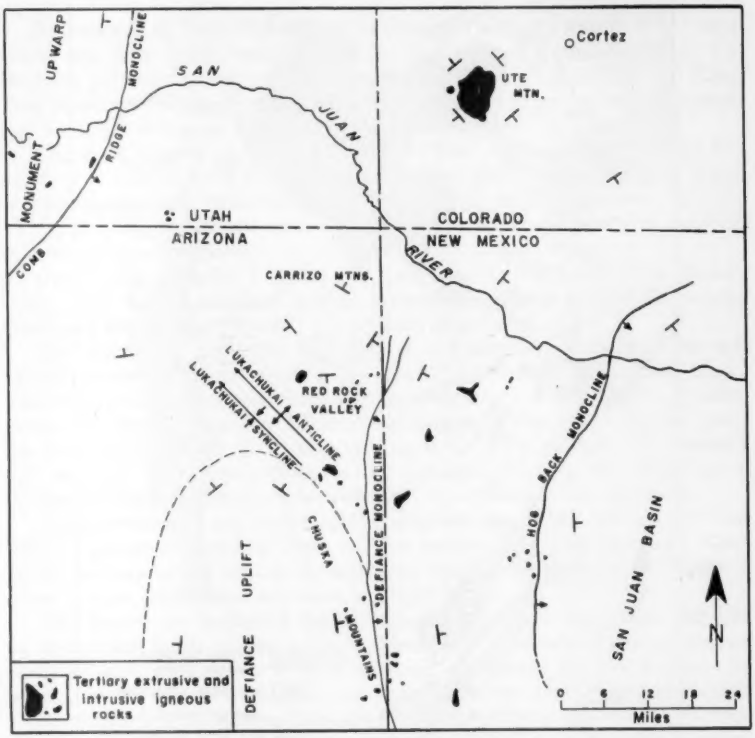

FIG. 1. Index and regional tectonic map, Lukachukai Mountains area, Arizona. (After Luedke and Shoemaker.)

Evidence for Pliocene volcanic activity may be found in the Hopi Buttes volcanics 150 miles to the southwest. These are dated middle-to-upper Pliocene by mammalian fossils in the associated lake beds of the Bidahochi formation (22). Basalt dikes, sills, plugs, and flows in the Chuska Mountains, in Red Rock Valley, and along the east flank of the Carrizo Mountains (Fig. 1) are of a composition quite similar to that of the Hopi Buttes rocks.

The volcanics are intruded into, and may be locally interbedded with, the Chuska sediments of Pliocene (?) age.

Williams (22) states that intrusions in the Chuska Mountains and Red Rock Valley followed no pattern. That is true within a restricted area, but

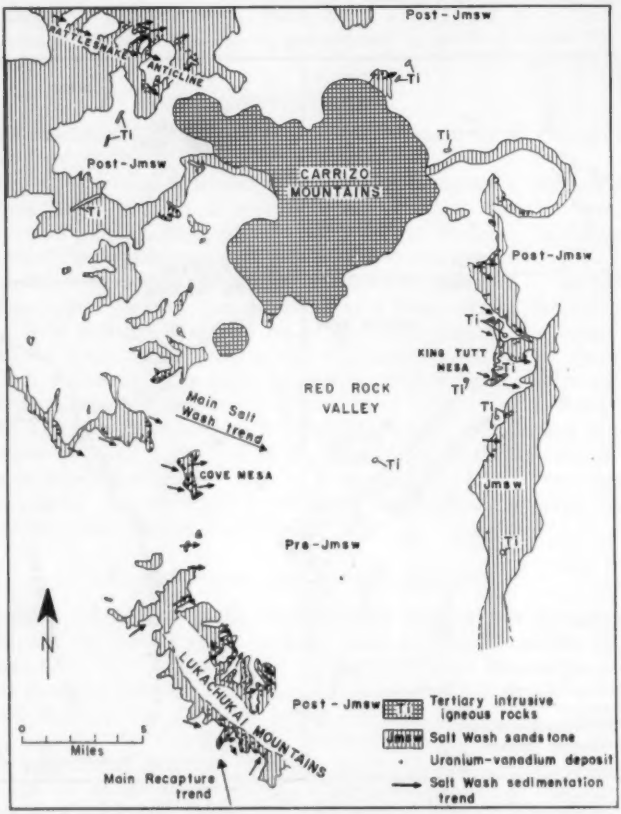

FIG. 2. Sedimentary trends and ore deposits of Salt Wash sandstone, Lukachukai Mountains area, Arizona.

Figure 1 shows a general limitation of intrusions to a north-trending belt on either side of the Defiance monocline, across the Chuska Mountains, Red Rock Valley, and the east flank of the Carrizo Mountains. The pattern suggests that igneous activity is related to the Defiance monocline. The monocline is believed to overlie a fault in basement rocks.

The numerous intrusions effected only minor contact metamorphism and no related uranium mineral concentrations have been found. Recent drilling in the East Carrizo area disclosed a cluster of small ore bodies that are intersected by a basalt dike. Available information indicates that the ore is pre-basalt intrusion, i.e., pre-Pliocene.

ORE DEPOSITS

Distribution of Ore.—The richer and larger uranium deposits of the area are in the Salt Wash sandstone of the Lukachukai Mountains (Fig. 2). Deposits of lesser grade and extent occur in the same formation at King Tutt Mesa east of the Carrizo Mountains, at Cove Mesa to the southwest, and on the Rattlesnake anticline to the northwest.

The Salt Wash member is a friable to firm sandstone with calcite cement; it is fine- to very fine-grained. In mineralized areas, the Salt Wash is impregnated with carnotite ($K_2O \cdot 2UO_3 \cdot V_2O_5 \cdot 3H_2O$), vanoxite ($2V_2O_4 \cdot V_2O_5 \cdot 8H_2O$), and lesser quantities of black uranium oxides and brightly colored calcium vanadates.

Ore Bodies.—Figure 3 shows the ore bodies in the Lukachukai Mountains. The Salt Wash-Bluff contact outlines the higher part of the mountains, and the various "mesas" are actually ridges.

Ore, except for negligible quantities at widely spaced intervals, does not extend northwest of the dashed line drawn from Mesa 6 to Step Mesa. This line is the approximate boundary between facies of Salt Wash: massive sandstones on the west and sandstone-mudstone on the east. Farther east, the Salt Wash member is missing because of Tertiary erosion. The dashed line through Two Prong Mesa is the approximate zone of change to a mudstone-minor sandstone facies in which no significant ore is found.

Concentration of ore bodies in the sandstone-mudstone facies (the "ore belt") suggests a cause and effect relation between host-rock and ore. Generally, portions of the ore belt in which no ore bodies are shown in Figure 3 bears a thick overburden and have not been tested.

The largest ore bodies of the Lukachukai Mountains are about 350 feet by 90 feet and rarely exceed 4 feet in thickness. A variable extent of barren rock, or rock with subgrade mineralization, surrounds the ore bodies. In general, the larger dimensions of ore are concordant with bedding, although sharp transection of bedding is locally common. Where the ore shows such discordance it is said by the miners to "roll" and the ore body itself is called a roll. A few rolls are roughly cylindrical, apparently associated with a carbonized log. Most rolls, however, only approach a cylindrical form and have no definite center. The size and shape of some ore bodies is controlled by "trash-piles." The term applies to accumulations of carbonized plant fragments, and the effect of such accumulations is apparent in rich mineral concentration. Not all trash piles contain ore, although most are mineralized.

Relation of Ore to Structure.—The Lukachukai Mountains are adjacent to a sharp anticlinal flexure and the mineralization of the Rattlesnake area

(Fig. 1) occurs on an anticline. However, structural features have exercised no apparent control on the trend or position of individual ore bodies in the Lukachukais or on the Rattlesnake anticline. Inasmuch as structural features must exercise some regional control on ground water movement, the structures in both areas may be of indirect importance in localizing ore.

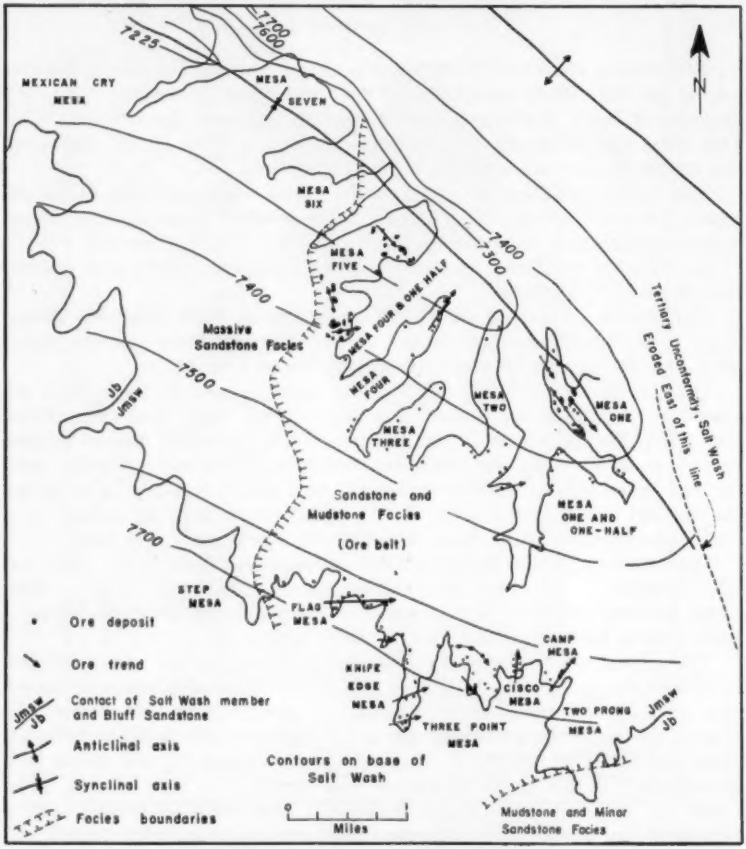

FIG. 3. Ore deposits, ore trends and sedimentary facies, Lukachukai Mountains, Arizona.

Figure 3 shows structure contours drawn on the base of the Salt Wash sandstone from surface and subsurface control points spaced from 500 to 1,000 feet apart along the north and south rims of the mountains. The plunging anticlinal axis trends about N 45° W toward Mexican Cry Mesa, where

it swings abruptly northward and dies out within one mile. The southeastern termination of the anticline is covered by Tertiary sediments. The adjacent plunging synclinal axis follows much the same pattern: it trends northwest across the mesas and loses its identity beyond Mexican Cry.

It has been suggested (12) that, following the Laramide Revolution, moving ground water leached previously deposited uranium and transported it down dip into areas of flat or reversed dip. There the uranium was precipitated. As Figure 3 indicates, there is no apparent relation of the position, or trend, of ore bodies to the local folds. No deposits are known in the flattest part of the syncline, across Mesa 7 and Mexican Cry, where ground water would have collected. Detailed structure maps in areas of close-spaced drilling show no relation of the deposits to minor changes in dip or strike. It appears that structural traps are not a significant control of uranium deposits on the Lukachukai Mountains. The same conclusions apply to those areas around the Carrizo Mountains which have received detailed study.

Relation of Stratigraphy to Ore Deposits.—Lithologic changes in the Salt Wash sandstone, both local and regional, bear an important relation to ore accumulation. As early as 1921, Coffin (4) suggested that uranium deposits in southwestern Colorado occur in the thicker sandstone sections of the Salt Wash member. Weber (20) presented a lithofacies map of the Salt Wash which showed that ore-bearing areas contain 40 to 60 percent sandstone. Bain (2) said that "carnotite deposits occur where shale makes up about half of the stratigraphic section of the Salt Wash member." Dodd (6) agreed with Bain and emphasized that the number of individual shale beds as well as the percentage of shale is important in directing solution flow. Weir (21) recognized that in the Uravan Mineral Belt an ore-bearing sandstone is commonly thicker than 40 feet and is gray or limonitic-brown in color. McKay (14) noted that favorable sandstones in the same region are lenticular. Stokes (19), as a result of mapping in the Thompsons area of eastern Utah and around the Carrizo Mountains, concluded that ore bodies are more common along the flanks of paleostream channels than elsewhere, and that the mineral deposits are commonly elongated parallel to Salt Wash stream flow.

Craig, et al (5) mapped the original distribution and thickness of the Salt Wash and other Morrison members as shown, in part, on Figure 4. The basin of Salt Wash deposition appears to have been bounded on the northeast by the old Uncompahgre positive area and on the west by the nascent Mesocordilleral geanticline. The position of the southern boundary of the basin cannot be considered the north flank of the old Defiance positive area because a thick section of Recapture sediments (which interfinger with, and overlie, the Salt Wash) was deposited across the present Defiance uplift (Fig. 4). The Lukachukai Mountains lie close to the southern depositional edge of the Salt Wash and within the zone of intermingling of Salt Wash and Recapture streams. It is not surprising, then, that the Salt Wash stratigraphy of the Lukachukai Mountains exhibits abrupt lateral changes over short distances.

The character of Salt Wash sedimentation in the Lukachukai area is the

same as that in the Uravan Mineral Belt of southwestern Colorado, but the scale is smaller. In the Lukachukai region individual sandstone lenses are thinner, narrower, and shorter; intervening mudstones are thinner; the ore bodies are generally smaller.

Figure 2 shows the outcrop of Salt Wash sandstone, the dominant sedimentary trends within the Salt Wash, and the location of ore deposits in the Carrizo and Lukachukai areas. The geology of the Lukachukai area was mapped by various Atomic Energy Commission geologists, whereas the rest

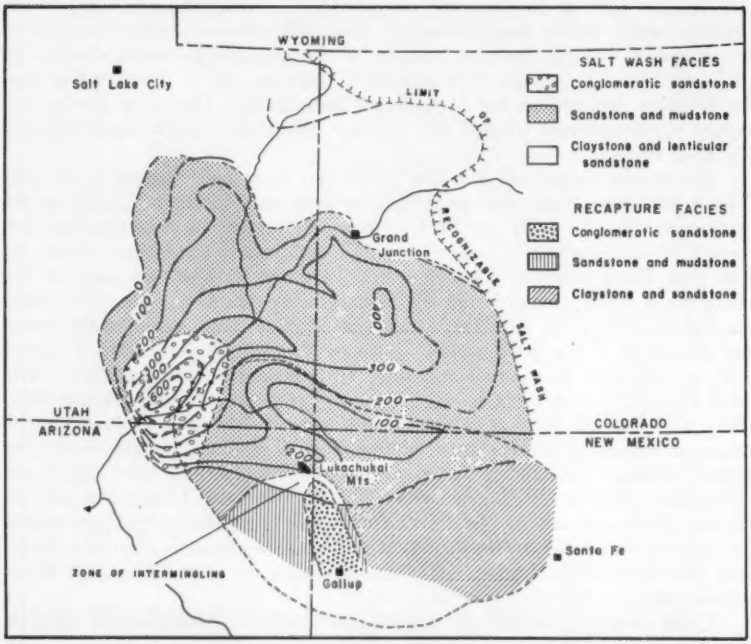

FIG. 4. Isopach and facies map of Salt Wash sandstone and facies map of Recapture shale.

of the map was made by Stokes. Sedimentary structures around the Carrizo Mountain show a dominant southeast trend in conformity with the regional picture shown on Figure 4 (5). In certain areas, particularly those of heavy concentration of ore deposits, the sedimentary trends curve northeast. Stokes (18) explained the concentration of ore bodies on those curves as a reflection of carbonaceous material deposited on the outside of a stream bend.

In the Salt Wash, two dominant stream directions (southeast and north) extend across the Lukachukai Mountains. It appears that the two trends are

a reflection of two major directions of deposition; one spreading southeast from the source of Salt Wash sediments, the other encroaching northward from the source area of the Recapture sediments (Figs. 4, 2). The separate trends, together with combinations of both, may be present across lateral distances of a few thousand feet. The confluence, hence confusion, of sedimentary trends appears to have created abrupt permeability changes and these may account, in part, for the favorable ore-trap conditions in the strata now exposed on the Lukachukai mesas.

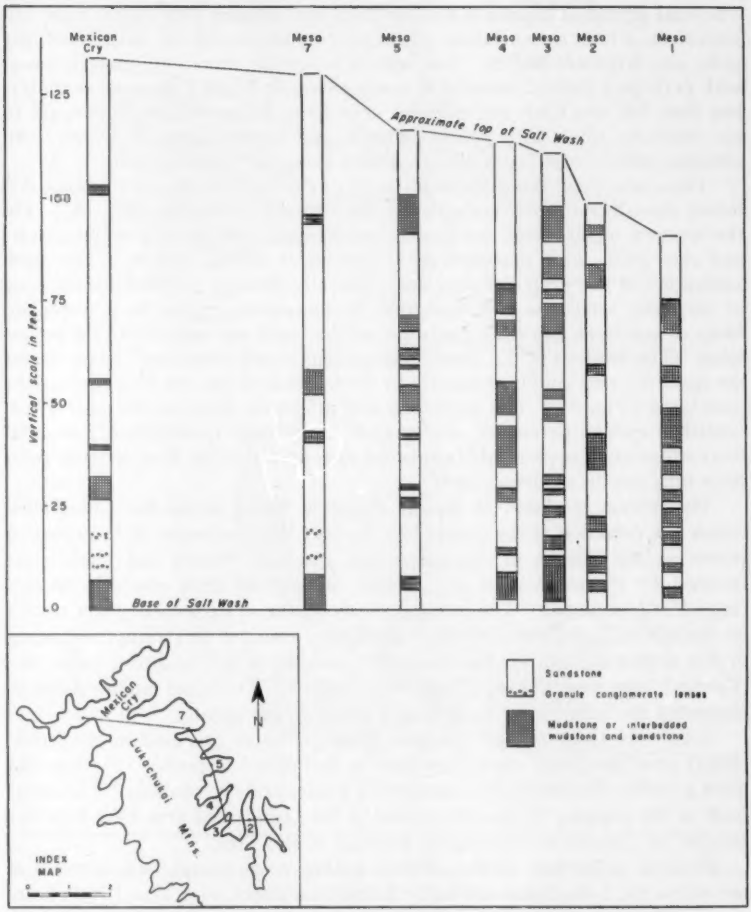

FIG. 5. Salt Wash cross section, Lukachukai Mountains, Arizona.

The Ore Belt.—The north to northeast trending ore belt across the Lukachukai Mountains (Fig. 3) is apparently related to lithologic changes in the Salt Wash. Massive sandstone cliffs on the western, barren mesas give way to distinct sandstone ledges separated by mudstone or thin mudstone-sandstone slopes on the eastern, ore-bearing mesas (Fig. 5).

The Salt Wash at Mexican Cry is about 135 feet thick and is about 90 percent sandstone with persistent lenses of granule conglomerate and abundant clay galls in the lower part of the section. Two, and in some places three, thin mudstone zones occur within the section. Traces of carnotite are present. The total section at Mesa 5 is 115 feet thick and contains only 70 to 75 percent sandstone, at least six mudstone zones, no conglomerate, lesser amounts of clay galls, and large ore bodies. The section is similar across the eastern mesas with perhaps a general increase in mudstone. At Mesa 1 the total section is less than 100 feet thick and contains only 40 to 50 percent sandstone, six to ten mudstone zones, little coarse material, and carries large ore bodies. An identical west-to-east facies change occurs along the southwest rim.

There are, then, three different facies of the Salt Wash, representing different depositional environments, on the Lukachukai mesas (Fig. 3). On the western mesas thick, continuous sandstones, with granule conglomerate and clay galls, were deposited by a fast-water stream system. The thick sandstones of the western mesas grade laterally through an intermediate zone of lenticular sandstone and mudstone on the eastern mesas to a floodplain facies of mudstone and stray sandstone on the south and east side of the mountains. The location of the "lenticular sandstone and mudstone" facies across the eastern mesas conforms exactly to the location of the ore trend across the same area (Fig. 3). The sandstone and mudstone facies of the Salt Wash contained enough permeable sandstone to carry large quantities of ore solutions and enough impermeable mudstone to concentrate the flow of those solutions into certain sandstone beds.

The unique condition of rapidly changing facies across the Lukachukai mesas is a reflection of the abrupt loss, by Salt Wash streams, of transporting power as the margin of deposition was reached. Sands and muds were dumped by the overloaded and braided streams as their channels became choked with sediment. The unusual concentration of carbonized plant matter on the eastern Lukachukai mesas is probably a result of this abrupt unloading of fine sediment. An increase in $CaCO_3$ cement in the sandstone cores was observed from west to east. Bain (2), assuming a uranium sulfate solution, suggested the influence of $CaCO_3$ as a precipitating agent.

Local Ore Controls and Guides.—Most guides to ore used in the Lukachukai area have been used elsewhere in Salt Wash deposits. Fischer (8) gives a rather comprehensive summary of guides and ore controls. However, most of the mapping techniques applied in the Lukachukai area have been developed by Commission geologists working in this area.

Detailed subsurface studies of core drilling areas reveal local controls of ore within the Lukachukai ore belt. Lithofacies maps (Figs. 6 and 7) indicate permeability variations which influenced solution movement; color-maps show

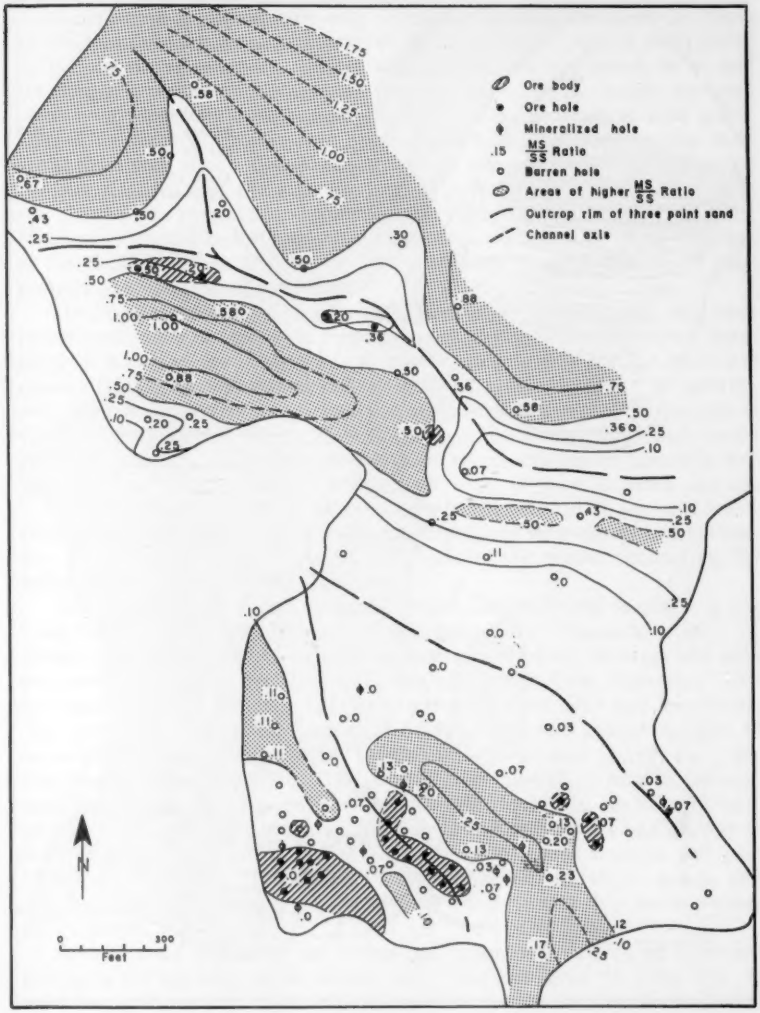

FIG. 6. Mudstone-sandstone ratio map of Three Point sand, Three Point Mesa, Lukachukai Mountains, Arizona.

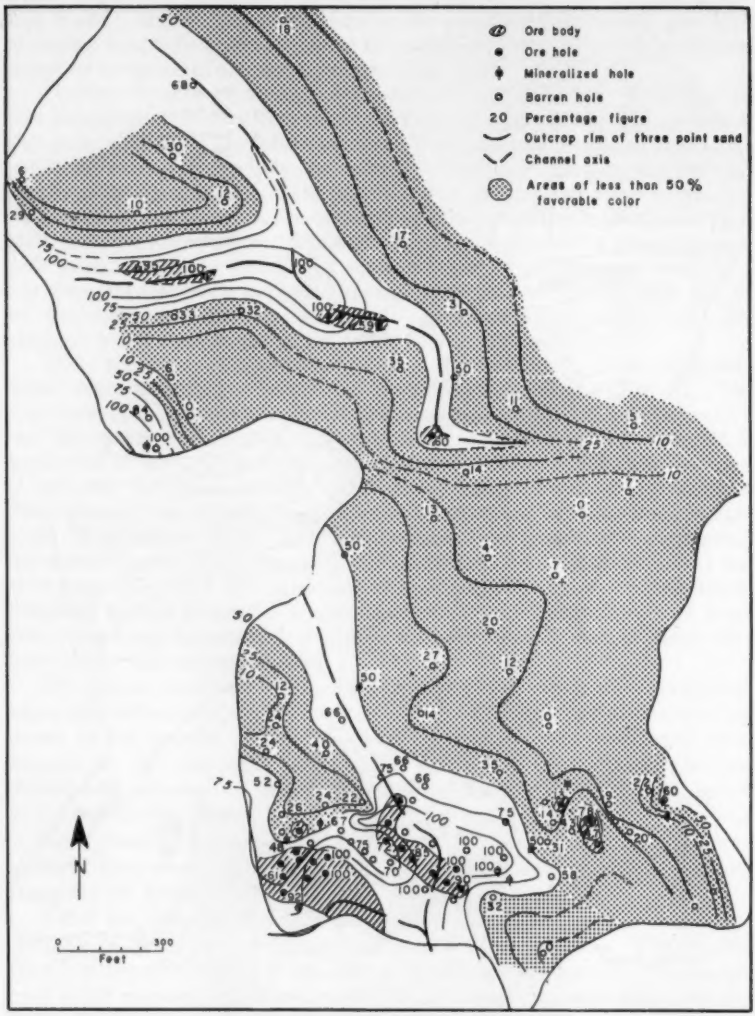

FIG. 7. Isopercentage of favorable color sand, Three Point Mesa, Lukachukai Mountains, Arizona.

zones of alteration. Both types of maps can be used to evaluate the favorability of the Salt Wash.

A mudstone-sandstone ratio map of the ore-bearing sandstone on Three Point Mesa (Fig. 6) shows two large, elongate ore bodies lying in, and parallel to, the old stream channels. Stated another way, the ore bodies lie in, and are elongated parallel to, the trend of permeability. The two bodies are separated by a mud zone of low permeability and both lie close to mud zones. East of the large ore bodies, two small deposits lie along the opposite flank of the main mud zone. One of the deposits is elongate parallel to sedimentation but the shape of the other has not been outlined. A narrow channel across the north part of the mesa has not yet been defined closely by drilling (because of excessive depth) but it appears that ore bodies lie along the flank of the channel, rather than in the center, and are elongate parallel to sedimentation, i.e., to the channel trend.

The importance of color as a guide to Salt Wash ore bodies has long been recognized. Ore occurs most commonly in gray or limonitic-brown sandstone; it is rare in red sandstone. Moreover, mudstone layers and seams are commonly gray in the vicinity of ore; elsewhere they are red. In general, gray color is considered to be alteration of the original red by the passage of ore-bearing solutions. Figure 7, a color map of the Three Point Sand, shows a typical situation. Contours are drawn on the percentage of favorably colored (gray or limonitic-brown) sand in the unit. It may be noted that ore is restricted almost entirely to zones that contain more than 50 per cent favorable color. The zones of favorable color correspond very closely to the channels shown on the facies map, but differ in that the central channel on the facies map is missing on the color map.

Sub-surface maps of drill core data from many different localities in the Lukachukai-Carrizo area show that favorable color "channels" (gray or brown) almost invariably follow the paleostream channels, whereas red sand is commonly found in the floodplain areas adjacent to those channels. Core inspection suggests that this red sand is slightly more silty and less friable than gray sand, hence less permeable. Thus, the color change appears to coincide with permeability paths. Where a channel sand is red, as is the sand in the central channel on Three Point Mesa (Fig. 6), it may be assumed that the channel was less permeable than other channels, or that the ore-solution did not enter that particular channel. The practical applications of these facts are: (1) color is a guide to ore and can be mapped and projected, (2) favorable color zones generally follow permeability zones, and (3) ore bodies are elongate parallel to color trends just as they are to permeability trends.

Several small low-grade ore bodies and numerous mineralized holes are known in the favorable color zone of unit "AD" on Mesa 4½ (Fig. 8). It must be significant that each ore body is either on the flank of the favorable color zone and adjacent to red sand, or abuts against local, pod-like masses of red sand.[1] Northward, the favorable color zone "bottlenecks" sharply to

[1] Two small "contour islands" of red sand, omitted from drawing, lie 2 inches from left and 1¼ inches above bottom.

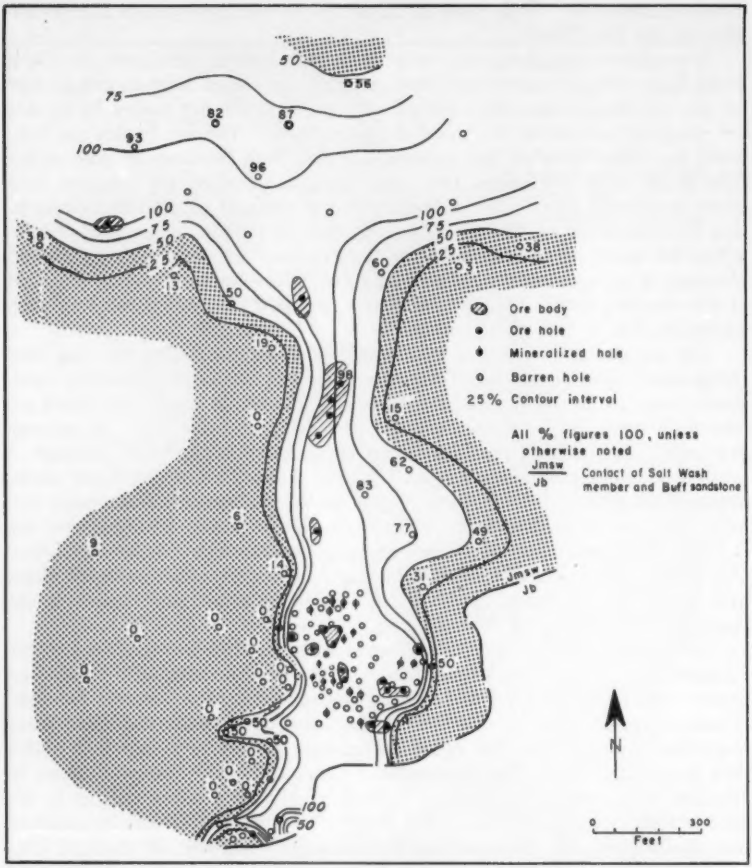

FIG. 8. Isopercentage of favorable color sand, A D sand unit, Mesa 4½, Lukachukai Mountains, Arizona.

a width of 250 feet. Along the "neck," several drill holes cut exceptionally thick, high-grade ore zones. Restriction of the favorable color to a narrow channel suggests a concentration of solution-flow there and hence a concentration of ore. In the wider zone, in the south half of the map, mineralization is dispersed except in the local areas adjacent to a relatively impermeable red sand. Changes in permeability apparently exerted significant control on the flow of solutions, causing diversion, damming and concentration.

Rapid lateral variation of color, and presumably permeability, is a charac-

teristic of the ore-bearing sandstone beds on the Lukachukai Mountains. In contrast, rapid lateral color variation is generally lacking in the sandstone beds of the Carrizo area, except at King Tutt Mesa where significant ore bodies have been found. Persistent gray sands appear to be relatively unfavorable because in them the mineral concentration tends to be dispersed.

METHODS OF EXPLORATION

The lithofacies maps and other similar maps have demonstrated several practical guides to ore in the Lukachukai area. In the search for ore, it is of particular significance that:

1. Ore bodies are elongate parallel to sedimentation
2. They tend to occur along the flanks of channels
3. They occur in gray or limonitic-brown sandstone adjacent to red sandstone
4. They tend to occur in groups or clusters

On the Lukachukai drilling project, maps of the lithologic channels and the favorable color channels have been drawn from wide-spread holes to indicate the probable location of favorable ground. When a channel is found, drilling has been continued in that favorable ground. Experience suggests that in wide channels the most favorable areas are near the flanks. The location of offset (development) holes around discovery holes has been guided by the rule that the ore bodies are elongate parallel to sedimentation. Holes drilled behind outcroppings of ore have been planned according to the same principles. Sedimentary trends have been determined from cross-bedding and lineation (18), and the ore trend then projected in the same direction.

U. S. Atomic Energy Commission,
Grand Junction, Colo.,
Nov. 23, 1954

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AGE AND SEDIMENTARY ENVIRONMENTS OF URANIUM HOST ROCKS, COLORADO PLATEAU

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ABSTRACT

On the Colorado Plateau, uranium mineralization has been found in 32 sedimentary units that range in age from Pennsylvanian to Tertiary, and in a Tertiary monzonite porphyry. Ore has been produced from 22 of these units. Host rocks represent all major sedimentary environments except glacial. The wide variation in age and depositional environments of the host rocks suggests an epigenetic origin for uranium ore on the Colorado Plateau.

INTRODUCTION

PROSPECTING on the Colorado Plateau has resulted in the discovery of uranium ore, or mineral concentrations, in numerous sedimentary units and in a monzonite porphyry. In 1952, Riley and Shoemaker (1) listed 18 uranium-bearing formations. Since that time an intensified search has increased the number of mineralized horizons on the Plateau to 32 (Table 1). If this effort is sustained, more discoveries will doubtless continue to be made in horizons not heretofore recognized as ore-bearing. At least five such discoveries were made during the past year. Jurassic formations still account for the greatest production of ore, but production from Triassic units is increasing rapidly, and it is anticipated that, in the near future, notable production will come from rocks of Cretaceous age.

In order to present a general picture of the variety of uranium occurrences, one deposit is described for each rock unit in which strong mineral concentration or ore has been discovered on the Colorado Plateau. In addition, an estimate of the production potential for the stratigraphic unit is included in each description, unless otherwise specified. Except where stated, the terms "mineral concentration" and "ore" herein refer to a grade of 0.10% U_3O_8 or greater, a magnitude on the order of 700 times the average content of sedimentary rocks given by Goodman and Evans (2).

ACKNOWLEDGMENTS

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DESCRIPTION OF URANIUM OCCURRENCES

Hermosa Formation (Pennsylvanian).—The Bald Eagle mine is one of several contiguous uranium-vanadium mines in the marine Hermosa limestone located on the northeast flank of the Gypsum Valley anticline, about 13 miles southwest of Naturita, Colorado. At this locality, the Hermosa is composed of thin lenticular gray limestone beds with shale partings. The beds have been overturned to the southwest and form a steeply-dipping hogback. For several miles along this hogback mineral concentrations occur intermittently. Carnotite appears to be localized along closely-spaced irregular fractures that give the rock a high permeability.

The Hermosa formation is regarded as having a fair production potential.

Rico Formation (Pennsylvanian).—Yellow uranium minerals occur in a fluvial sandstone of the Rico formation in Cane Springs Canyon about 10 miles southwest of Moab, Utah. Bleaching of the red sandstone accompanies the uranium minerals which impregnate the sandstone along a fault.

No significant production is expected from the Rico formation, except possibly in some faulted areas.

Supai Formation (Permian).—Copper-uranium-vanadium ore is found in the Middle (?) Supai formation at the Ridenour mine, about 30 miles north of Peach Springs, Arizona. The host rock is fluvial red sandstone and shale, bleached to light gray-green in the vicinity of the ore. The uranium occurs sporadically in the hanging wall of a copper vein.

No significant uranium production is anticipated from the Supai formation.

Hermit Shale (Pennsylvanian).—In Hacks Canyon, a north-rim tributary of the Grand Canyon, thirty-nine miles southwest of Fredonia, Arizona, copper-uranium-phosphate ore has been mined from a sandstone member of the Hermit shale. The host rock is a fluvial red sandstone that is bleached in the vicinity of the ore.

No significant production is anticipated from the Hermit shale.

Coconino Sandstone (Permian).—Copper-uranium-lead ore, associated with abundant limonite and pyrite, is found in the Coconino sandstone at the Orphan Lode mine, which is about 1,200 feet below the south rim in the Grand Canyon and about 1½ miles from Bright Angel Lodge. The host rock is an eolian sandstone. The ore occurs along fracture zones, and the uranium component appears to be intimately associated with fine-grained galena.

The Coconino sandstone has a fair production potential.

DeChelly Sandstone (Permian).—Carnotite ore with associated vanadium minerals is mined from the DeChelly sandstone at the Monument No. 2 mine in Monument Valley, 20 miles southeast of Mexican Hat, Utah. Immediately below the base of a paleostream channel, ore occurs in the cross-bedded

eolian sands and along fractures. This channel was incised into the DeChelly and later filled with Shinarump conglomerate which is now rich in uranium at this locality.

No significant production is anticipated from the DeChelly, except where leaching may have removed ore from overlying Shinarump channels and developed secondary accumulations in the underlying eolian sandstone.

TABLE 1

Uranium-Bearing Rock Units of the Colorado Plateau

Period	Formation or Unit*	Total uranium production from unit	Depositional environment of host
TERTIARY	Monzonite Porphyry		Igneous Stock
	Browns Park fm		Fluvial
	Bidahochi fm		Lacustrine
	Uinta fm		Fluvial
	Wasatch fm		Fluvial
CRETACEOUS	Pictured Cliffs ss.		Fluvial
	Mesaverde gr		Fluvial
	Dakota ss.		Fluvial & Lagoonal
	Burro Canyon fm.		Fluvial
JURASSIC	Brushy Basin sh.		Fluvial
	Westwater ss.		Fluvial
	Recapture sh.		Fluvial
	Salt Wash ss.		Fluvial
	Bluff ss.		Eolian
	Summerville fm.		Lacustrine
	Curtis fm.		Marine
	Todilto ls.		Lacustrine
	Entrada ss.		Eolian
	Carmel fm.		Marginal marine
	Navajo ss.		Eolian
JURASSIC ?	Kayenta fm		Fluvial
TRIASSIC	Wingate ss.		Eolian
	Chinle fm.		Fluvial
	Shinarump cgl.		Fluvial
	Moenkopi fm.		Fluvial
PERMIAN	Cutler (Big Buck) fm.		Fluvial
	Kaibab ls.		Marine
	DeChelly ss.		Eolian
	Coconino ss.		Eolian
	Hermit sh.		Fluvial
	Supai fm.		Fluvial
	Rico fm.		Fluvial
PENNSYLVANIAN	Hermosa fm.		Marine

Mineralized — Production under 1,000 tons — Production over 1,000 tons

* Rock units are shown in approximate time sequence

Kaibab Limestone (Permian).—Copper-uranium mineral concentrations are found in the uppermost zones of the marine Kaibab limestone at the Willaha rail siding north of Williams, Arizona. The beds are mineralized on the crests of anticlines where mineral concentration appears to be associated with travertine.

No significant production is anticipated from the Kaibab limestone.

Cutler Formation (Permian).—Uranium-vanadium ore has been mined intermittently, since 1948, from the Cutler formation at the Big Buck claims in Big Indian Wash, about 32 miles southeast of Moab, Utah. On the Big Buck claims the fluviatile Cutler formation contains two arkose lenses about 100 feet below the upper contact. In these lenses ore has two modes of occurrence: as disseminated carnotite and becquerelite; and as scattered concretions, one-half to 4 inches in diameter, which are rich in uranium, vanadium, and lime. Some enrichment occurs along fractures.

Production potential of the Cutler formation is regarded as fair.

Moenkopi Formation (Triassic).—Uranium-copper ore is found in the Moenkopi formation at Elk Ridge on the Notch No. 5 claim, 34 miles west of Blanding, San Juan County, Utah. Uraninite is associated with hydrocarbons and mud galls in a fine-grained, well-sorted, cross-bedded, gray to brown sandstone and siltstone. The beds appear to be fluvial in origin but littoral sediments underlie them.

The production potential of the Moenkopi formation is considered poor except locally where the formation contains hydrocarbons.

Shinarump Conglomerate (Triassic).—Carnotite ore is mined from basal Shinarump conglomerate at the Skyline mine south of the Oljetoh Trading Post, Utah, within the Monument Valley area, near the Arizona state line. The host rock is a fluvial quartz-pebble and mud-pellet conglomerate which fills a channel incised into the Moenkopi formation. A basic volcanic dike crosses the channel near the orebody.

Throughout southeastern Utah and northeastern Arizona, numerous channels, cut into older formations and filled with Shinarump conglomerates and sandstones, contain excellent uranium deposits.

The production potential of this formation is excellent.

Chinle Formation (Triassic).—At the Mi Vida mine in Big Indian Wash, approximately 32 miles southeast of Moab, Utah, black uranium-vanadium ores occur in the lower part of the Chinle formation. The ore deposit is on the west flank of the faulted Lisbon Valley anticline, and the host rock is a fluvial arkosic sandstone which contains disseminated uraninite.

The production potential of the Chinle formation is excellent.

Wingate Sandstone (Triassic).—Uranium-vanadium mineral concentrations are found in the Wingate sandstone at Temple Mountain, in the southeast corner of the San Rafael Swell, Emery County, Utah. Ore occurs within a collapse zone, and is scattered throughout the Wingate sandstone for a distance of 300 feet laterally from the fractured area. The greatest concentration of the ore is about two-thirds of the way up from the base of the Wingate sandstone. The ore is associated with asphalt and iron gossan and occurs in thin lenses of bleached, dolomitized, eolian sandstone.

Although ore has been mined from this occurrence, no significant production is anticipated from the Wingate sandstone.

Kayenta Formation (Jurassic?).—On the Big Chief claim in Roc Creek Canyon, about 11 miles northwest of Naturita, Colorado, uranium-vanadium mineral concentrations are found in the Kayenta formation. Here the Ka-

yenta is a fluvial deposit of fine- to medium-grained, light gray, cross-bedded sandstone with occasional thin, gray-green mudstone partings. Carnotite occurs both impregnated in the sandstone and as concentrations along closely spaced fractures and bedding planes. Malachite and azurite are sporadically distributed in the ore. The Big Chief mine is in a graben bounded by complex faulting.

No significant production is expected from this formation.

Navajo Sandstone (Jurassic).—Copper-uranium mineral concentrations are found in the Navajo formation about 2 miles west of Red Mesa Trading Post, Utah. The host rock is a massive light-red eolian sandstone. Mineralized pods occur along fractures that parallel a basic dike lying 500 feet to the southeast.

No significant uranium production is anticipated from the Navajo sandstone.

Carmel Formation (Jurassic).—Uranium mineral concentrations, associated with copper minerals, are found in the Carmel formation north of Saucer Basin, about thirty miles south of Green River, Utah. Mineral concentration occurs in greenish-gray laminated bleached siltstones near the top of the formation. Deposits are small and scattered, and assay less than 0.10% U_3O_8.

The production potential is regarded as fair.

Entrada Sandstone (Jurassic).—Carnotite ore, associated with black vanadium minerals, is currently produced at the Joker mine, about 21 miles west of Naturita, Colorado. The mine is located on the crest of a small anticline in the floor of Little Gypsum Valley, a topographic feature which is the result of a graben formed in the crestal portion of a salt anticline. Mineral concentration is disseminated in the upper 30 feet of eolian Entrada sandstone. Abundant fracturing appears in the mine. In addition, there are several inactive large, low-grade deposits in the Entrada sandstone on the Colorado Plateau.

The production potential of the Entrada sandstone is considered poor under present economic conditions.

Todilto Limestone (Jurassic).—Tyuyamunite-uraninite ore is mined from the Todilto limestone at Haystack Butte, a few miles northwest of Grants, New Mexico. The host rock is a lacustrine limestone that contains tyuyamunite and minor uraninite along minute silty laminae. It is suggested that ore distribution is controlled by drag folds in the upper Todilto and possibly by fractures. Fluorite is closely associated with some of the ore.

The Todilto limestone has an excellent production potential.

Curtis Formation (Jurassic).—Approximately 2 miles northwest of Skull Creek, Colorado, several copper-vanadium-uranium prospects and mines occur in a thin bedded sandstone facies that comprises the basal portion of the marine Curtis formation. This unit contains varying amounts of organic material and disseminated copper, iron, vanadium, and yellow uranium minerals. The orebodies and mineralized areas are all on the steeply tilted southern limb of the Skull Creek-Willow Creek anticline.

No significant production is expected from this formation.

Summerville Formation (Jurassic).—Carnotite-uraninite ore is mined from the lowermost zones of this formation at Haystack Butte, northwest of Grants, New Mexico. The host rock is a lacustrine sandstone. Orebodies occur at the unconformable contact of the Summerville formation with the Todilto limestone.

No significant production is expected from the Summerville formation except locally as extensions of underlying Todilto orebodies.

Bluff Sandstone (Jurassic).—Carnotite mineral concentration associated with black vanadium minerals is found about 10 feet above the base of this sandstone at a point 2 miles northwest of the Carrizo Mountains in northeastern Arizona. The host rock is an eolian sandstone in which mineralized lenses follow crossbedding.

No significant production is anticipated from the Bluff sandstone.

Salt Wash Sandstone (Jurassic).—Carnotite ore with associated black vanadium minerals has been mined extensively from the Salt Wash member of the Morrison formation in a great many localities on the Colorado Plateau. Accordingly, a generalized description of mode of occurrence is given. The ore is generally found disseminated in a permeable, fine- to medium-grained, cross-bedded, fluvial sandstone which contains carbonaceous material and is interbedded with gray-green mudstone lenses. The ore may occur at different stratigraphic horizons within the Salt Wash. The ratio of vanadium to uranium varies from 1:1 to 20:1. Although secondary uranium minerals are predominant, uraninite deposits have been found in Salt Wash.

The potential for continued production is excellent.

Recapture Shale (Jurassic).—Carnotite ore with associated vanadium minerals is mined from a zone 50 feet below the upper contact of the Recapture shale member of the Morrison formation, on the Enos Johnson claim, 8 miles west of Sanastee, New Mexico. The host rock of interbedded mudstone and sandstone is fluvial in origin. Ore is bedded and surrounded by bleached zones.

The recapture shale has a good production potential in this area.

Westwater (?) Sandstone (Jurassic).—Carnotite ore is mined from the Westwater (?) sandstone member of the Morrison formation at the Jackpile mine, near Paguate, Laguna Indian Reservation, New Mexico. The host rock, a fluvial sandstone, is intruded by a thin diabase sill Pliocene (?) in age. The major ore deposit forms a blanket immediately beneath the sill, although some ore is found above the sill. The close spatial relationship of sill and ore and a rather strong alteration of the sill along its contacts suggest a genetic relationship between sill and ore.

The Westwater (?) sandstone has an excellent production potential in this area.

Brushy Basin Shale (Jurassic).—Carnotite is mined from sandstone beds in the Brushy Basin (?) shale member of the Morrison formation at the Poison Canyon mine, about 15 miles north of Grants, New Mexico. The host rock is a fluvial, conglomeratic sandstone which contains bedded ore and ore-pods in association with asphaltite.

The Brushy Basin has an excellent production potential in this area.

Burro Canyon Formation (Cretaceous).—Uranium mineral concentration occurs near the base of the Burro Canyon formation on Berties Beauty No. 1 claim in Baboon Basin, about 7 miles northwest of Naturita, Colorado. The host rock is a fluvial, conglomeratic sandstone containing thin lenses of green mudstone, abundant carbonaceous trash, and scattered silicified logs. Carnotite-type minerals are disseminated in the sandstone with higher concentrations in brown carbonaceous trash zones.

No significant production is expected from this formation in this area.

Dakota Sandstone (Cretaceous).—Uranium has been found in two vastly different lithologic types of the Dakoata sandstone in New Mexico. It has been mined from black carbonaceous shale beds of the Dakota formation on the Hogback monocline east of Gallup, New Mexico. The host rock is believed to have been deposited in a lagoonal environment. Mineralogy of the uranium in the shale is not known.

Carnotite ore has been mined from fluvial sandstone beds of the Dakota formation at the Silver Spur mine, about 12 miles north of Prewitt, New Mexico. The ore is confined to bedding planes and fractures in the vicinity of carbon trash accumulation.

The Dakota formation has a fair production potential.

Mesaverde Group (Cretaceous).—Carnotite ore has been found about 150 feet above the base of the Mesaverde group, on the northeast rim of Black Mesa at a point about 12 miles north of Black Mountain Trading Post, Navajo Reservation, Arizona. The host rock is a fluvial sandstone in which bedded ore is associated with abundant carbon trash.

The Mesaverde group has a good production potential.

Pictured Cliffs Sandstone (Cretaceous).—Uranium mineral concentration is found in the Pictured Cliffs sandstone about 20 miles northwest of Farmington, New Mexico. The host rock is a fluvial, arkosic sandstone. Megascopic uranium minerals have not yet been observed.

The Pictured Cliffs sandstone is considered to have a fair production potential.

Wasatch Formation (Tertiary).—Carnotite ore is found at the base of the Wasatch formation 6 miles north of Thompson, Emery County, Utah. Secondary uranium minerals are found coating carbonaceous logs in cross-bedded, poorly-sorted, sand lenses which fill scours in fluvial sandstone beds. Limonite staining is prevalent, and calcite is the dominant cement in the host rock.

The production potential of the Wasatch formation in this area is considered fair.

Uinta Formation (Eocene).—The Uinta formation is a sequence of variegated shales interbedded with lenticular, gray and buff, fluvial sandstones. Most of the limited production has come from small mines located between Myton and Ouray, Utah. Ore appears to be restricted to paleostream channel sands containing abundant carbonaceous material. Uranium is contained within the carbonaceous material, in megascopically unidentifiable minerals. Malachite and azurite are found with all uranium occurrences observed in the area.

Production potential for the Uinta formation is regarded as fair.

Bidahochi Formation (Pliocene).—Carnotite concentrations have been found 40 miles north of Holbrook, Arizona, in central Navajo County. The most strongly mineralized rocks are water-laid, pyroclastic, fine to coarse tuffaceous debris with fragments of volcanic glass in the coarser material. Associated with the pyroclastic rock is a light cream, thin-bedded marl that is mineralized to a lesser degree. Mineralization has been confined to diatremes that occur within or are associated with disturbed sediments in a collapsed area. Deposits are small and chemical assays vary from 0.03 to 0.20% U_3O_8.

No significant production is expected from this formation.

Browns Park Formation (Pliocene, Miocene?).—The Browns Park formation covers an area exceeding 1,000 square miles in northwestern Colorado and northeastern Utah and underlies a vast area northward into Wyoming. Much of this formation is slightly radioactive—containing on the order of 0.001 to 0.003 percent U_3O_8—and certain restricted areas average between 0.10 and 0.20 percent U_3O_8. Several deposits containing yellow uranium minerals, concentrated along fractures in sandstone, occur ½ mile north of Juniper Springs, Colorado.

The production potential of this formation is considered fair.

Monzonite Porphyry (Tertiary).—Uraninite-uranophane ore is found in veinlets injected into a monzonite porphyry plug in the Henry Mountains of Garfield County, south central Utah. Fluorite and fine-grained quartz intergrowths are associated with the uraninite stringers.

The extent of mineral concentration is unknown.

CONCLUSIONS

Uranium deposits of the Colorado Plateau occur in sedimentary units of almost every geologic epoch from Middle Pennsylvanian to Middle Tertiary. The host rocks reflect all major sedimentary environments except glacial: namely fluvial, eolian, lacustrine, lagoonal, and marine. In addition, uranium is found in an igneous rock. The bulk of ore produced to date has come from fluvial sediments, although significant production has come from rocks of lacustrine and lagoonal origin. To illustrate the variety of uranium occurrences, several examples of structurally controlled ore deposits have been cited. These are clearly epigenetic. Moreover, it is felt that even for the deposits lacking structural control, the occurrence of ore in rocks of such wide stratigraphic distribution and such diversity of depositional environment can most logically be explained by an epigenetic origin.

U. S. Atomic Energy Commission,
Grand Junction, Colo.,
Nov. 22, 1954

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ORE CONTROLS IN SANDSTONE URANIUM DEPOSITS OF THE COLORADO PLATEAU

ROBERT J. WRIGHT

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ABSTRACT

Marked lithologic control characterizes most uranium deposits in sandstone formations of the Colorado Plateau. Deposits in rocks ranging in age from the Cutler formation of Permian age to the Wasatch formation of Eocene age are primarily in 1) fluvial sandstones which, 2) contain carbonized plant matter, 3) are light-colored or gray, rather than red, and 4) contain feldspar or mica. In addition, 5) sandstones that are interbedded with or interfinger with shales or mudstones are particularly favorable. These features are also characteristic of most sedimentary copper deposits.

Most uranium deposits in sandstone formations show no immediate connection with tectonic features, but a general clustering of orebodies around large positive structures is noted. The reason for this is not clear.

It is postulated that at least some of the uranium in the ores was derived from the same source as the host rocks. In this light the sandstone uranium deposits may be the continental analogue of uranium-rich marine black shales and phosphorites. Sedimentary copper deposits may have had a similar origin. Uranium moving seaward in streams, during erosion of a land mass, may be fixed on the continent in certain favorable fluvial environments.

INTRODUCTION

Deposits in sandstone beds of the Colorado Plateau are the source of most of the uranium and vanadium mined in the United States. The deposits have

been known since 1898 and have been worked at various times for their uranium, radium, or vanadium content. Most production has come from the Salt Wash sandstone member of the Morrison formation, which is Jurassic in age.

This paper summarizes briefly ore controls and ore guides that characterize deposits in the Morrison formation and discusses in more detail certain aspects of the lesser known deposits in rocks of other ages. The discussion follows a dual classification of ore controls—sedimentary (i.e. host rock) controls and structural controls. The source material has come from study of deposits in

Age	Formation	Thickness (feet)	Character	Uranium Production
Eocene	Wasatch fm.	3,000 ±	Varicolored shale, sandstone and limestone	Minor occurrences
Cretaceous	Mesaverde gr.	1,000	Light colored sandstone and gray shale; coal-bearing	Minor producer
	Mancos sh.	2,000 - 5,000	Gray shale	
	Dakota ss.	50-200	Gray and brown sandstone and shale	Minor producer
	Burro Canyon fm.	50-250	Light-colored sandstone, green and maroon shale	
Jurassic	Morrison fm.	300-500	Brushy Basin shale member: varicolored shale and some sandstone	Minor producer
		200-400	Salt Wash sandstone member: light-colored sandstone and red mudstone	1. Most important producer
	Summerville fm.	50-400	Red and gray shale, thin sandstone	
	Curtis fm.	0-250	Glauconitic sandstone and greenish shale	
	Entrada ss.	50-1,000	Light-colored and red massive sandstone	Important vanadium producer; minor uranium
	Carmel fm.	0-600	Red earthy sandstone and gray shale	
	Navajo ss.	0-200	White sandstone	
Jurassic (?)	Kayenta fm.	0-300	Red sandstone	
Triassic	Wingate ss.	0-400	Red massive sandstone	
	Chinle fm.	100-500	Red and red-brown shale and sandstone	3. Third most important producer
	Shinarump cgl.	0-100	Light-colored conglomerate and sandstone	2. Second most important producer
	Moenkopi fm.	0-1,000	Brown and red shale and sandstone	Minor producer
Permian	Cutler fm.	0-6,000	Light-colored sandstone and red and gray shale	Minor producer

FIG. 1. Generalized geologic section of western Colorado and eastern Utah. Todilto limestone, which carries ore in the Grants, New Mexico, district, underlies the Summerville formation, the Curtis formation being absent. (Modified after U. S. Geological Survey.)

the Colorado Plateau, although occasional reference is made to deposits elsewhere.

GENERAL SETTING OF THE DEPOSITS

Figure 1 is a generalized geologic section of southwestern Colorado and eastern Utah. The rocks are mainly continental, including light-colored sandstones, which are fluvial and eolian in origin, red sandstones, and mudstones and shales of various colors. A few formations are mainly of marine origin: namely, the Carmel formation, the Curtis formation, and the Mancos shale.

Strata that contain uranium deposits are indicated in the column headed "Uranium Production" (Fig. 1). Ore from the Salt Wash member of the Morrison formation has been the mainstay of the uranium-radium-vanadium industry for many years and this sandstone unit still yields about 60 percent of all domestic uranium production. Most of the mines are in western Colorado (Fig. 9). Second in importance is the Shinarump conglomerate, which supplies about one-quarter of current production. In third place is the Chinle formation. The Entrada sandstone has yielded important amounts of vanadium, but the uranium content of the ores is low. Minor uranium production has come also from the Cutler formation, the Brushy Basin shale member of the Morrison formation, the Dakota sandstone, the Mesaverde group, and the Wasatch formation. Other formations of the Colorado Plateau contain occurrences of minor significance or are thought to be barren.

SUMMARY OF SEDIMENTARY ORE CONTROLS IN THE MORRISON FORMATION

Several observers have pointed out the importance of sedimentary features in localizing uranium deposits in the Salt Wash sandstone member of the Morrison formation. Large scale facies changes in the Salt Wash appear to have been effective in localizing mineral districts. Small scale sedimentary features have influenced localization of individual deposits and groups of deposits.

On a regional scale most deposits have been found where the Salt Wash member contains about equal amounts of sandstone and mudstone. Webber (39) estimates that most production has come from regions with 50 to 70 percent sandstone. More recent work by Craig et al. (8) suggests that in areas favorable for ore, the Salt Wash member contains 40 to 55 percent sandstone. In the Lukachukai Mountains, Arizona (22), exposures permit observation of an area where the Salt Wash changes character rapidly from a massive sandstone facies to a sandstone-mudstone facies to a mudstone-minor sandstone facies. A mineral belt, containing most of the proven deposits, coincides with the sandstone-mudstone facies belt (Fig. 2).

On a small scale other associations between orebodies and certain sedimentary features have been recognized. In western Colorado most orebodies found during drilling by the U. S. Geological Survey (40) are in sandstone beds more than 40 feet thick, in which the sandstone is brown rather than red, which is the prevailing color of barren rock. The mineralized sandstone typically contains abundant fossil plant debris. Mudstone below and within

the ore-bearing sandstone is gray in the vicinity of ore rather than red as it is in barren areas.

Areas where Salt Wash sandstones are lenticular and discontinuous are generally more favorable than areas where the sandstone units are widespread and uniform. In the Uravan and Gateway districts of Colorado (23) the

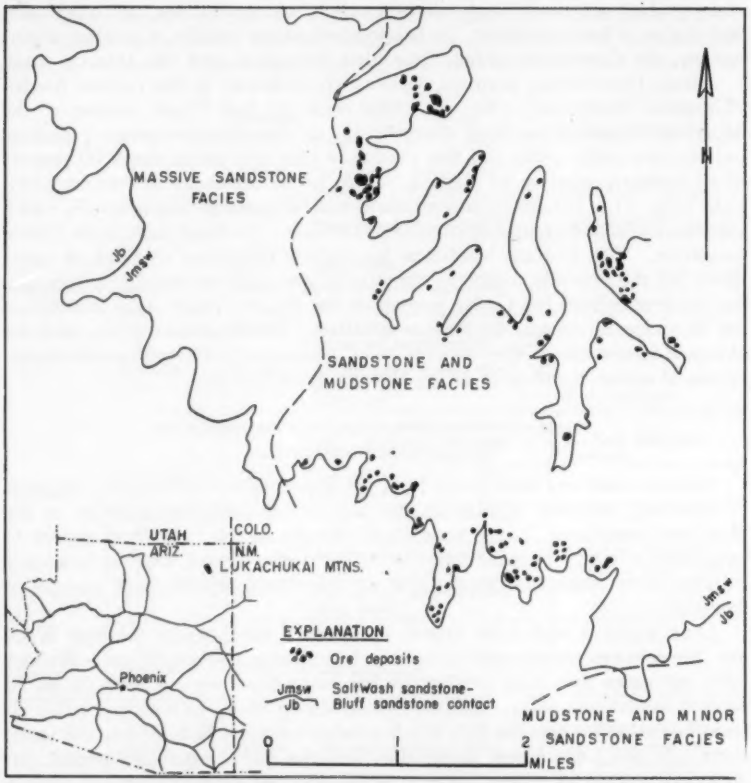


FIG. 2. Facies control of an ore belt in the Lukachukai Mountains, Arizona. Here the Salt Wash sandstone overlies the Bluff sandstone. Because of overburden exploration to date has been largely limited to a zone immediately back of the outcrop of the Salt Wash sandstone. (After Masters.)

largest and richest known orebodies are in areas where the ore-bearing sandstone is dominately lenticular. The petrography of the Salt Wash has been compared (15) in three widely separated areas—Moab district, San Juan County, Utah; Montezuma Canyon area, San Juan County, Utah; Lukachukai Mountains, Apache County, Arizona. This study suggests that the mining

productivity of these areas corresponds directly with the amount of lithologic variation in the ore-bearing sandstone. In the Lukachukai Mountains (22) orebodies are located along the flanks of paleostream channels, a transitional sedimentary environment wherein lithology changes abruptly from sandstone to mudstone.

Many orebodies are elongate parallel to the direction in which streams that deposited the Morrison formation are believed to have flowed. This direction can be inferred from measurements of the orientation of current lineation (32), cross-bedding inclination, ripple marks, and the azimuth of fossil logs. For example, in the Thompson area, Utah, the favored orientation of elongate orebodies is N 50°–60° E (33). Many measurements of cross-bedding directions here suggest that the Salt Wash streams flowed in the same direction.

Recognition of the association of ore with sedimentary features has proved of practical application in exploration for new orebodies (42).

CHARACTERISTICS OF DEPOSITS IN OTHER FORMATIONS

Considerable uranium production now comes from orebodies in formations other than the Morrison. A few of the deposits have been worked for a

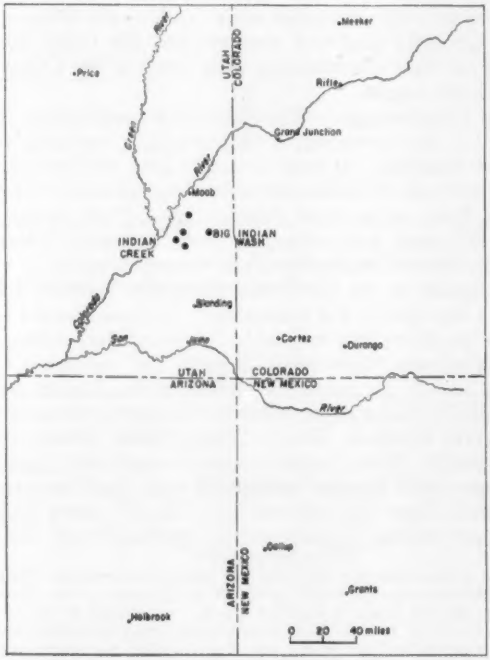


FIG. 3. Index map of uranium deposits in the Cutler formation. (After Shoemaker and Luedke.)

number of years, but most were unknown until after World War II. Their study has yielded much new information about the occurrence of uranium ores in sandstone. The geologic setting of typical deposits in various formations is described below.

Cutler Formation.—Known uranium deposits in the Cutler formation are small and limited in distribution (Fig. 3). Although comparatively rare, the deposits aptly illustrate certain conditions favorable for uranium deposition.

Deposits in Big Indian Wash, San Juan County, Utah, have been worked intermittently since 1948. Here the Cutler formation consists of red mudstones, siltstones, thin white marls, and lenses of coarse, arkosic sandstone. Uranium minerals are limited to the arkose lenses, which contain pebbles of granite and fragments of orthoclase, quartz, and mica. The lenses are up to 28 feet thick and several hundred feet long along the outcrop (9). Five such lenses are known as Big Indian Wash and all carry uranium minerals; the enclosing red beds have, so far, proven barren. Similar deposits are known in Indian Creek and Lockhart Canyon, also in San Juan County.

The favorability of uranium for light-colored, arkosic, micaceous beds in the Cutler formation is striking because this type of lithology is not widespread within the Cutler of eastern Utah. Typically the formation consists of clean, white, cross-bedded eolian sandstone units—such as the White Rim sandstone member, the DeChelly sandstone member, and the Cedar Mesa sandstone member—and red shale and mudstone units—such as the Organ Rock tongue and the Hoskinnini tongue.

Shinarump Conglomerate.[1]—The Shinarump conglomerate, in view of its wide extent, is a thin formation; it ranges from a vanishing point to more than 100 feet in thickness. It consists of light gray and buff quartz sandstone and conglomerate with discontinuous beds of mudstone and siltstone that are mostly gray. These rocks are of fluvial origin. Plant material is common, both as petrified wood and carbonized plant remains. Feldspar is locally abundant, as in White Canyon, San Juan County, Utah.

Uranium deposits in the Shinarump are widely distributed (Fig. 4) and vary greatly in size, grade, and mineralogy. Uranium occurs as pitchblende and as various secondary hydrous sulphates, phosphates, oxides, and silicates. In the unoxidized zone, base metal sulphides are common. Carnotite and vanadium minerals are common in the Monument No. 2 mine, Apache County, Arizona. Asphaltic materials are abundant in places and constitute most of the ore at Temple Mountain, Emery County, Utah. Many ores carry only uranium compounds; others contain values in copper and vanadium.

Among these varied deposits perhaps the most significant common feature is the association of ore with channel fills (Fig. 5) where Shinarump sediments occupy paleostream channels cut into the underlying Moenkopi forma-

[1] Stratigraphic studies currently under way by the U. S. Geological Survey suggest that Shinarump conglomerate may not extend north of the junction of the Green and Colorado Rivers. Uranium deposits north of this line are now considered to be contained within a sandstone unit in the lower part of the Chinle formation. For consistency with published reports the present paper follows earlier literature that describes this ore-bearing unit as Shinarump conglomerate. The details of stratigraphic interpretation do not materially affect the present discussion of ore controls.

FIG. 4. Index map of uranium deposits in the Shinarump conglomerate. Deposits north of the junction of the Green and Colorado Rivers may be contained within a lower Chinle sandstone rather than within the Shinarump conglomerate (see footnote). (After Shoemaker and Luedke.)

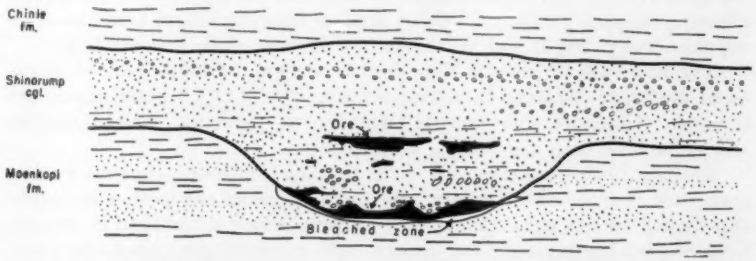


FIG. 5. Idealized cross section of an ore-bearing paleostream channel in the Shinarump conglomerate. Below a channel the red Moekopi formation is commonly bleached for a thickness of several inches to a foot or more.

tion. These channels range from a few feet to several hundred feet in width and some have been traced by drilling for several miles. Where channels are present at the base of the Shinarump, they provide the locus for orebodies, and commonly the lower portion of the channel-fill carries the highest ore values. Fossil plant matter is an important localizer for uranium within the channels. At the Happy Jack mine, San Juan County, Utah (26), and at the Delta group, Emery County, Utah, pitchblende replaces wood, preserving the cell structure.

Chinle Formation.—Since 1950, uranium ore has been mined from sandstones of the Chinle formation in the Silver Reef district, Washington County, Utah. Discoveries at Big Indian Wash, San Juan County, Utah, have pushed the Chinle formation into third place production among uranium-bearing formations of the Plateau. Many of the important orebodies discovered in the past two years are in the Chinle formation.

In the Silver Reef district, the uranium is contained in the Tecumseh sandstone, a unit in the upper part of the Chinle formation. "The Tecumseh sandstone is a medium-grained micaceous, thin- to thick-bedded buff and lavender sandstone about 60 feet thick. Its terrestrial origin is indicated by fluvial cross-bedding, by lensing of shale beds within the member, by clay galls or 'pebbles' and by fossil reeds and rushes" (36). In addition to uranium, the ores contain vanadium, copper and, commonly, several ounces of silver per ton.

During 1950, uranium ores were discovered by Indian prospectors in Chinle sandstones of northern Arizona. The ore is confined to lenses of tan sandstone within a sequence of varicolored shales and mudstones. The ore-bearing sandstone can be distinguished from similar, but barren, red sandstone by its characteristic color. Most of the ore is associated with abundant plant matter, generally in the form of compressed lignitic material on bedding planes.

The largest presently known Chinle deposits are in Big Indian Wash, San Juan County, Utah. Discovery of ore in the Chinle formation was made by C. A. Steen during 1952. The discovery drill hole passed through a 13-foot ore zone in a sandstone bed low in the Chinle formation. Further exploration resulted in development of the Mi Vida orebody, one of the largest domestic uranium producers. Other deposits have since been found by drilling elsewhere in Big Indian Wash, and the reserves of the area are large.

The host rock for the Mi Vida deposit is a gray, medium-grained, micaceous sandstone cemented by calcite and iron oxides (9). Fossil plants are common. Uraninite, tyuyamunite, montroseite, carnotite, melanovanadite, and pyrite have been identified in ore specimens.

Entrada Sandstone.—Deposits of the Entrada formation have been worked mainly for their vanadium content; the uranium values are too low to justify exploitation for this metal alone. The Entrada, where mineralized in western Colorado, is a fine-grained, cross-bedded, light-colored to gray sandstone (13). In eastern Utah, to the west of the known deposits, it becomes a deep red, fine-grained earthy sandstone. The main ore mineral is a vanadium-bearing hydrous mica with films of carnotite along fracture planes in the richer ore.

SUMMARY OF SEDIMENTARY ORE CONTROLS

Uranium deposits in sandstones of the Colorado Plateau are numerous and diverse in mineral character. During the first half of 1953, production was realized from more than 600 separate deposits. The orebodies are scattered through a wide geographic range and situated in varied stratigraphic and structural settings; yet most of the deposits, such as those described above, are in a characteristic lithologic setting that is distinguished by the following features:

First, the prevalent host rock is a sandstone of fluvial origin. In contrast, sandstones of marine and eolian origin are generally not mineralized.

Second, most of the host rocks are either arkosic or micaceous. Muscovite is the most common mica. Feldspar is particularly abundant in ore-bearing sandstone of the Cutler formation. The Salt Wash sandstone contains, on the average, 7 percent feldspar (8).

Third, most of the deposits are associated with fossil organic matter, and this material appears to have acted as a precipitation agent. Pitchblende re-

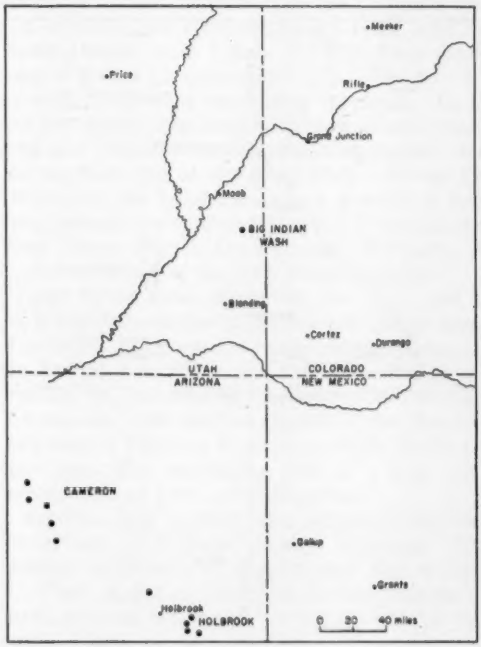


FIG. 6. Index map of uranium deposits in the Chinle formation. The Silver Reef district, in southwest Utah, is west of the area shown. (After Shoemaker and Luedke.)

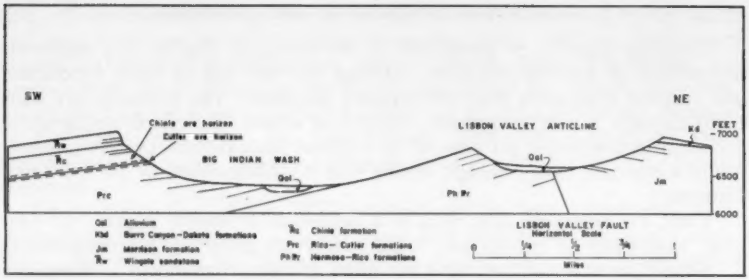


FIG. 7. Generalized cross section of Big Indian Wash, San Juan County, Utah.

placement of wood is common in some Shinarump deposits, and the association of pitchblende with fossil organic matter is almost universal.

Fourth, rocks immediately enclosing the orebodies are not red in color although in general the ore-bearing formation may be red away from the ore-

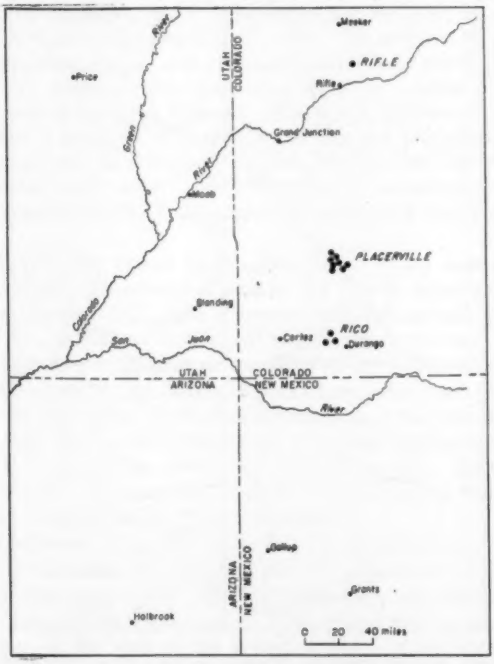


FIG. 8. Index map of vanadium-uranium deposits in the Entrada sandstone. (After Shoemaker and Luedke.)

bodies. Most host rocks immediately adjacent are gray, buff, tan, brown, pink, or lavender, but the abundant red rocks of the Colorado Plateau are rarely impregnated with uranium minerals. In most localities the characteristic colors appear to be primary; the non-red color suggests reducing chemical conditions during sedimentation. A few deposits, such as those in the Cutler formation of Lockhart Canyon, are contained within an envelope of tan rock in which the color boundary is sharply transgressive across the bedding and across lithologic contacts. This is believed to represent discoloration, due to the passage of mineralizing solutions, of rocks that were initially red in color.

Fifth, sandstones that are interbedded with, or interfinger with, mudstones and shales are particularly favorable for uranium mineralization.

All of the above features, with the possible exception of the characteristic color, are primary features.

SANDSTONE URANIUM ORES OUTSIDE THE COLORADO PLATEAU

Sandstone uranium ores with many of the above characteristics have been reported in parts of the United States outside the Colorado Plateau:

1. Deposits of carnotite and tyuyamunite are being mined in the Edgemont district, South Dakota, from Lakota and Fall River sandstones of the Inyan Kara group of Lower Cretaceous age (3). The host rock is buff to white sandstone with conspicuous channelling in places. In many deposits uranium minerals are closely associated with carbonaceous plant matter.

2. The Lakota and Fall River sandstones also contain ore in northeast Wyoming, in the northern end of the Black Hills. At the Carlile deposit, Cook County, Wyoming, the Lakota sandstone consists of medium to fine-grained tan arkosic sandstone with abundant seams of lignitic carbonized plant matter. The New Haven deposit, Cook County, Wyoming, is in medium- to fine-grained gray sandstone of the Fall River formation.

3. In the Powder River Basin, Wyoming, tan, pink, and brown arkosic sandstone of the Wasatch formation of Eocene age carries uranium minerals of ore grade. Love (20) has presented considerable evidence suggesting that the uranium was leached from radioactive tuff in the overlying White River formation and carried by downward moving waters into favorable host rocks in the Wasatch formation. At least one deposit of the Powder River Basin, in the Lost Spring area of Converse County, is within the Fort Union formation of Paleocene age. The ore-bearing rock is a gray, medium-grained, arkosic sandstone with small flecks of plant carbon.

4. Uranium deposits have recently been discovered in the Wind River formation of Eocene age, of Fremont County, Wyoming. The ore is contained within arkosic sandstone and conglomerate that is interbedded with gray mudstone. Plant carbon is important in localizing the ore of certain deposits; in others, greenish-tan, waxy, phosphatic material appears to have been a precipitant.

5. At the Garo deposit in Park County of central Colorado, uranium was mined prior to 1920 from the Maroon formation of Permian age (41). Here the Maroon formation, which is an eastern equivalent of the Cutler formation,

consists of red sandstone, conglomerate, shale and a few thin limestone beds. Uranium is associated with copper and vanadium minerals and the mineralization is thought to be confined to three beds of red to white to light buff, thin-bedded sandstone containing feldspar pebbles. The beds are within a stratigraphic interval of 150 feet.

6. At Mauch Chunk, Pennsylvania, carnotite deposits are presently being developed in the Pottsville conglomerate of Pennsylvanian age. Here the Pottsville (T. N. Walthier, personal communication) is a dark gray quartz conglomerate and quartzite. The sandstone is lenticular and contains carbonized plant remains.

7. Uranium occurrences are known in the Stockton formation of Triassic age in the vicinity of Flemington, New Jersey, and Doylestown, Pennsylvania. The Stockton is a pink arkosic pyritic sandstone with minor carbonaceous matter (T. N. Walthier, personal communication).

It is clear that sandstone uranium ores are strongly influenced by lithology, and uranium deposition was closely controlled by a favored host rock. In view of their broad geographic spread and wide geologic range, the deposits represent perhaps the most striking example of ore control by host rock that has been described.

Yet in the Colorado Plateau it is apparent that lithology, although very important, is only a partial clue in resolving the problem of why uranium deposits are where they are. Large volumes of apparently favorable rocks contain no known ore. Other geologic factors must have operated together with lithology to localize the deposits.

STRUCTURAL ORE CONTROLS

Control of uranium deposits by tectonic features is generally less obvious than control by sedimentary features. In many deposits no structural influence has been recognized. Like lithologic features, structural controls have been effective on both the local scale, in localizing individual orebodies, and on the regional scale, in localizing mineral districts.

A few deposits and groups of deposits appear directly related to faults and fault zones. A causal connection between an orebody and a fault can be best established, 1) where the minerals are concentrated along the fault plane and decline laterally outward from the fault, and 2) where mineralization has occurred at various stratigraphic levels along the fault zone. The Atomic King deposit, Cane Creek, San Juan County, Utah, exhibits both these features. Along a steeply dipping, east-trending fault, mineral concentration of ore grade is found in the Rico, Moenkopi, and Chinle formations. Where the fault plane is exposed by mine workings in the Chinle, it is apparent that mineralization has been concentrated along the fault. At Temple Mountain, Emery County, Utah, ore has been mined along a fault zone at various stratigraphic levels from the Shinarump conglomerate through the Wingate sandstone. Individual orebodies, however, do not seem to be concentrated along faults.

On a regional scale a general relationship between groups of deposits and certain major positive structures appears to be expressed by concentrations of deposits on the flanks of these structures. Four examples are described briefly below—Gypsum Valley anticline, Lisbon Valley anticline, San Rafael Swell, and the Zuni uplift. The spatial relationship between these structures and ore deposits is imperfectly demonstrated because the uplifts provide exposures of the ore-bearing strata, which results in a natural clustering of known deposits near uplifts. Comparable exposures away from the uplifts are not everywhere available for comparison purposes.

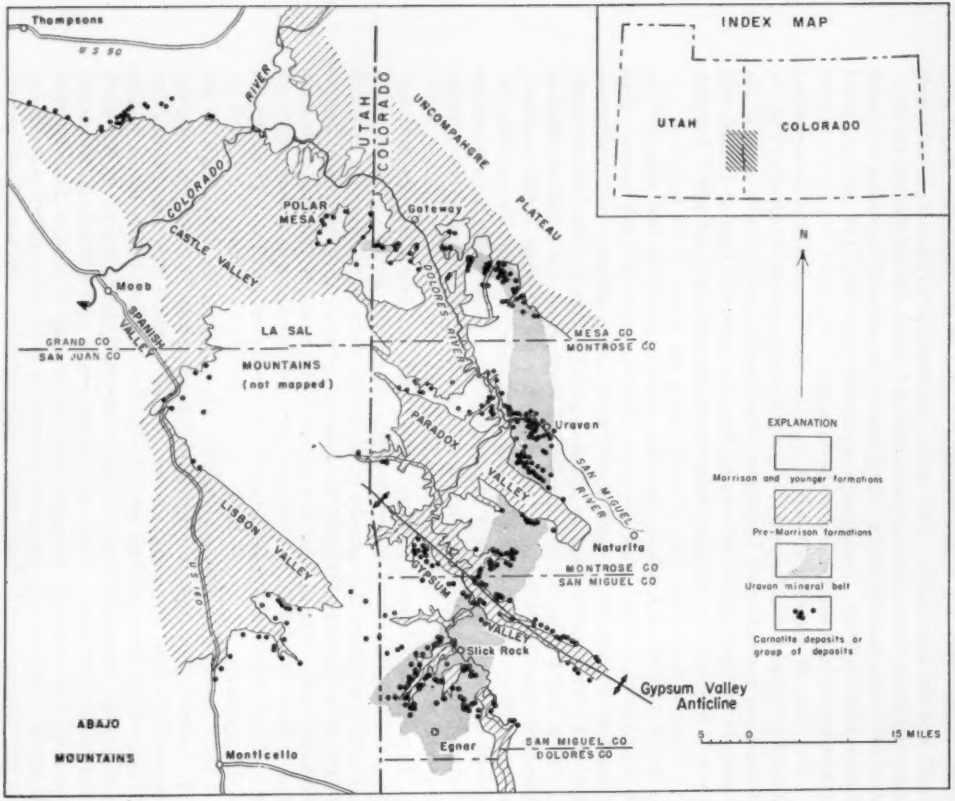
The Uravan mineral belt, which includes the largest and most numerous Morrison deposits, trends generally north through western Colorado (Fig. 9). It transects the dominant northwest structural pattern of this part of the Plateau. In most places the mineral belt has a width of about 5 miles, but where it intersects the Gypsum Valley anticline the belt is markedly widened. Ore deposits extend for some 25 miles along the flanks of the anticline.

Big Indian Wash has been described above as a locality that contains both highly important Chinle deposits and Cutler deposits of lesser value. Both formations are widely exposed to the west and northwest, but nowhere is there a known concentration of uranium metallization in these strata similar to that at Big Indian Wash. Big Indian Wash is on the southwest flank of the faulted Lisbon Valley anticline, which, like the Gypsum Valley structure, is one of the northwest-trending salt-cored anticlines that characterize the eastern part of the Colorado Plateau (Fig. 10). Like other nearby similar structures the Lisbon Valley anticline was probably active during the Triassic, when the ore-bearing beds were deposited (2).

The San Rafael Swell, Emery County, Utah, is a broad asymmetrical anticlinal uplift, probably of Laramide age. Along the flanks of the structure Shinarump conglomerate appears in an almost continuous exposure in which a number of important deposits are known, including the productive Temple Mountain area. The ore deposits of the Swell are larger and more numerous than proven deposits in the Shinarump conglomerate where exposed in an area of little structural deformation along the Green and Dirty Devil Rivers to the southeast.

The Grants, New Mexico, uranium district is on the north flank of the Zuni uplift. Here ores are known in the Jurassic Todilto limestone, the Jurassic Morrison formation, and sandstones of the Cretaceous Dakota formation. It has been pointed out (6) that individual orebodies in the Todilto limestone are elongate parallel to the local joint system typical of the north flank of the Zuni uplift. This relationship, along with the association of uranium ore with fluorite, is suggested as indicating a possible hydrothermal source for the ores. An alternate interpretation of joint control may be that the joint system guided downward moving solutions, which leached uranium from overlying mineralized Recapture and Dakota sandstones and deposited it in the Todilto to form the present ores.

The arcuate shape of the Uravan mineral belt, with the La Sal Mountains laccolithic mass on the concave side (Fig. 9), has led to the suggestion that the mineral belt may represent a peripheral zone around the intrusive. Other



MAP OF PART OF COLORADO AND UTAH, SHOWING THE PRINCIPAL DEPOSITS

FIG. 9. Map of part of Uravan Mineral Belt, showing widening of the belt along Gypsum Valley anticline. (After U. S. Geol. Surv. Bull. 988-A.)

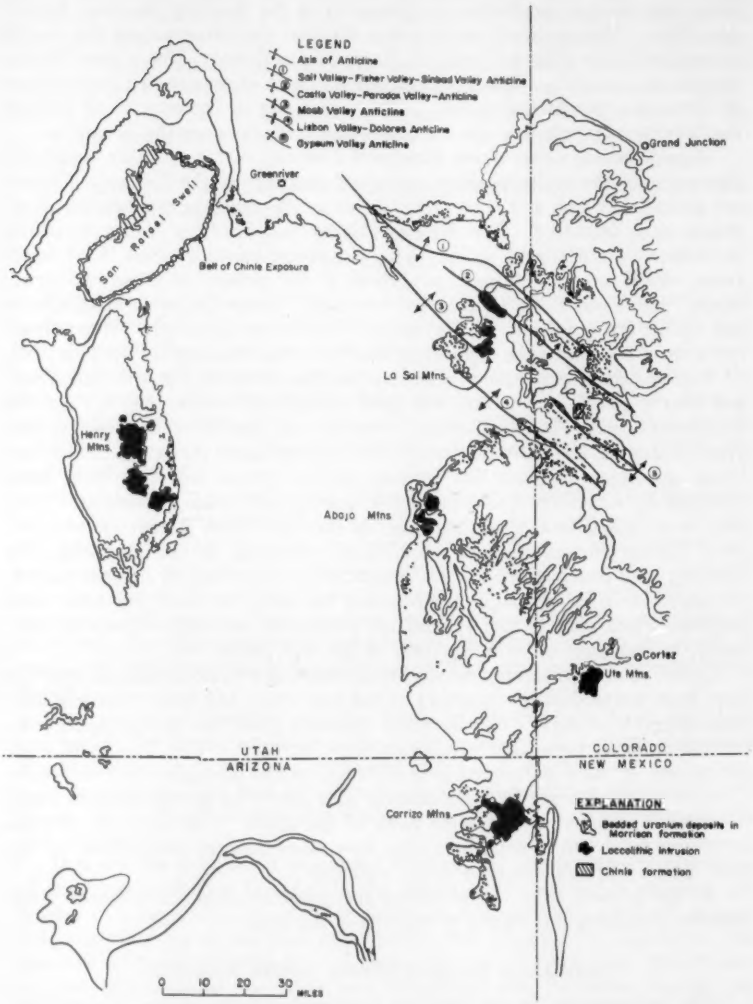


FIG. 9. Map of part of Uravan Mineral Belt, showing widening of the belt along Gypsum anticline. (After U. S. Geol. Surv. Bull. 988-A.)

FIG. 10. Outcrop belts of Morrison formation showing general distribution of uranium deposits. Prepared by M. V. Anthony from information by U. S. Geological Survey.

similar laccolithic intrusives, such as the Henry, Abajo, and Carrizo Mountains, also show a concentration of deposits in the flanking Morrison formation (28). The geometric relationship between the intrusive and the nearby mineralized zone differs in each of the areas mentioned. But a general conclusion can be drawn: the Morrison formation is especially favorable within 30 miles of a laccolith (Fig. 10). This is not due to exposure alone because the Morrison formation crops out over large areas between the laccoliths.

Significance of Large Scale Structural Controls.—It is probably significant that many of the major positive structural elements of the Colorado Plateau are geologically old, and some were active at the time the ore-bearing sandstones were deposited. The Gypsum Valley and Paradox Valley anticlines of western Colorado were active during the deposition of the Salt Wash sandstone, which has proven quite productive in the vicinity of these two structures. The Lisbon Valley anticline was active when the ore-bearing Cutler and Chinle formations of the Big Indian Wash were deposited. These structures, then, influenced the deposition, and hence the lithology, of the host beds.

One explanation of the relationship between orebodies in the Salt Wash and nearby positive structures has been offered by Stokes (34, 35) for the Rattlesnake area, Apache County, Arizona, and the Blanding district, San Juan County, Utah. Detailed analysis of sedimentation directions in the Salt Wash sandstone suggests that streams of Salt Wash time may have been deflected by structures that were active during Salt Wash deposition. This may have caused local disarrangement of the Salt Wash stream system, creating disordered sedimentation conditions, resulting in abrupt changes in lithology, and providing conditions favorable for deposition of organic matter. In other words, a lithologic environment favorable for ore may have been created. According to this explanation structural control is expressed indirectly, by influence on sedimentation of the host rocks.

Other structures around which ore deposits are localized do not seem to have been active during deposition of the host rock, and here other explanations appear necessary. The laccoliths obviously could not have affected sedimentation of the rocks into which they were intruded. The Zuni uplift does not appear to have influenced sedimentation of the Jurassic and Cretaceous formations, yet deposits in rocks of these ages appear to be concentrated along a restricted segment of the north flank of the uplift. The influence of such structures on uranium deposition may have been through their effect on the movement of hydrothermal or other solutions.

At the present state of knowledge the genetic connection between large positive structures and uranium deposits is not clear.

SIMILARITY TO SEDIMENTARY COPPER DEPOSITS

The sedimentary copper deposits constitute a large group of orebodies which, for the most part, are so similar in setting to the sandstone uranium ores that the only significant difference is the relative amount of the two metals. Some deposits contain both. The Happy Jack mine, San Juan County, Utah, was first worked for copper and later for uranium.

As summarized by Finch (10), the sedimentary copper ores are found in

fluvial sediments mainly of Permian to middle Mesozoic age. Although contained in a section of red beds, the deposits are immediately enclosed in light-colored or gray rocks. Most of the host rocks are arkosic or micaceous (14). Vegetal remains are common and appear to have been effective in localizing the ore mineral. The controls noted above appear effective regardless of the geographic location of the copper deposits and regardless of the age of the host rocks. Only a few deposits offer a suggestion of structural control.

It is apparent that the controls of sandstone uranium and "red-bed" copper deposits are strikingly similar.

GENETIC IMPLICATIONS

Noting the marked control of orebodies by sedimentary features, impressed by the general lack of structural control and by the limited nature of obvious hydrothermal effects, most early students of Morrision ore deposits favored a syngenetic origin for these deposits. The present position and form of the deposits would, according to this view, result from the combined effect of sedimentary deposition modified by diagenetic processes and later ground water action. Most published descriptions of the Plateau ores reflect this concept of genesis.

More recently a hydrothermal origin has been proposed. This thesis has been supported by the discovery of pitchblende in various deposits (27, 29) and by age determinations on the ore minerals (31). Uranium/lead and lead/lead ratio determinations indicate an age of about 60 million years for deposits in both Triassic and Jurassic rocks. This corresponds with Laramide time and suggests that uranium was introduced into the sediments at some time after their deposition and at about the same period as the emplacement of pitchblende veins of similar uranium/lead ratio in the Colorado Front Range.

Recognition of abundant volcanic debris within the Salt Wash sandstone and within the overlying Brushy Basin shale has led to a third suggestion that uranium may have been contributed to the Salt Wash by supergene solutions bearing uranium that had been leached from overlying tuffaceous sediments (38). Application of this theory to deposits in Wyoming has already been mentioned.

It is not the purpose of this paper to present a comprehensive discussion of the many problems involved in the origin of the sandstone uranium deposits. To the author, no present theory of genesis seems adequate to provide a mechanism of uranium introduction that explains the significant features of all types of orebodies. Indeed, the variations among the deposits suggest that uranium may have been introduced into the rocks through one or more of several possible mechanisms, so that the deposits bear the mark of more than one ore process. If this is true, the features of any single deposit would result from the peculiar combination of geologic activities that produced it. A multiple origin for sedimentary copper deposits has been advocated by Blanchard and Boswell (5).

The following discussion emphasizes one aspect of the syngenetic hy-

pothesis: a possible relationship between sandstone uranium deposits and a part of the geochemical cycle of uranium.

GENESIS AND THE URANIUM GEOCHEMICAL CYCLE

Investigators of Morrison deposits, generally favoring a syngenetic origin, suggested various source areas which could have simultaneously provided the clastics of the Salt Wash sandstone and the associated uranium and vanadium. Hess (18) postulates vein deposits of uranium in the source area. Argall (1) suggests that the uranium and vanadium came from the Permian Phosphoria formation, but Craig (8) points out that this would have involved movement transverse to the flow of Salt Wash sediments. Webber (39) suggests the Paleozoic Kaibab and Madison limestones, along with the Phosphoria formation, as possible source rocks.

To find concentrated uranium sources, such as older ore deposits, in the source area of all formations that are now known to contain sandstone ores is difficult: the formations were derived from many different land masses at many different times.

Is it possible, then, that uranium and its companion elements, vanadium and copper, were derived from a diffuse source which was available at many places and at many geologic times?

Hurley (19) has shown, by acid leaching tests and alpha particle analysis, that most of the radioactivity in granites appears to emanate from films of secondary salts on grain surfaces and incipient fracture planes, rather than from discrete minerals. In near-surface granites up to 80 percent of the radioactivity can be removed by short-time leaching with dilute acid solutions. In deep-seated granites the loss in radioactivity is less, suggesting that the change in form of the radioactive materials may be due to supergene weathering effects, which make radioactive minerals more available for solution.

It seems reasonable, then, that during weathering and erosion much of the radioactivity in an igneous mass would be available for removal by surface and ground waters. Igneous rocks did contribute some material to most of the sandstones which contain uranium in the Plateau, as evidenced by their common feldspar content, and may have provided uranium in the same way. Uranium, vanadium, and copper do move from land sources to the sea during weathering and erosion, and the three metals do precipitate out of solution under similar chemical conditions: these facts are evidenced by the deposition of all three elements in marine black shales and marine phosphorites, where the concentration is unquestionably syngenetic. The uranium content of these marine rocks is well known (24); in fact they contain a large part of the uranium in the earth's crust. Vanadium has been produced commercially from the black shales (21) and has been recovered as a by-product of fertilizer manufacture from the Phosphoria formation (25). The "Kupferschiefer," a bituminous shale of Germany, has been worked for copper and also contains uranium and vanadium, along with other metals (21). Although copper does not appear to be especially concentrated in the phosphates, it is present in trace amounts (25).

Furthermore, the chemical environment under which the black shales and phosphorites were deposited is quite similar to the environment in which the ore-bearing sandstones were laid down. Reducing conditions prevailed during deposition of the sandstones, as suggested by their color and the abundance of carbonized plant remains. Reducing conditions also characterzed deposition of the marine rocks (21) : pyrite or marcasite is common in the uranium-bearing black shales and carbon is abundant in both the shales and the phosphorites.

Carbon appears to play an important role in both sandstone ores and uranium-rich marine rocks, although its effect is not exactly known. In some uranium-bearing black shales the uranium content and the organic content vary together (4) and a similar relationship has been noted between uranium and organic matter in the Phosphoria formation (37).

It may be significant that the oldest sandstone uranium deposit (of the type described in this paper) known to the writer is in rocks of Devonian age, which gives the host rocks approximately the same geologic time span as coal beds. This may reflect the fact that prior to the Devonian, plant material and suitable type or quantity was not available on the continental surface to form coal or to provide the organic component which appears desirable for a favorable sandstone host rock.

In summary, it is suggested that at least some of the uranium in sandstone ores and the copper in sedimentary copper deposits may have had a common source. It is postulated that the uranium, vanadium, and copper of the ore deposits were derived from the same provenance as the enclosing sediments; that during the cycle of weathering and erosion these elements were removed in solution by surface and ground waters; that during the general seaward migration of the dissolved elements they were trapped on the continental surface in certain favored fluvial environments; and that the initial syngenetic concentration of metals was modified by diagenesis by ground water, and perhaps by hydrothermal solutions. In this light the sandstone uranium ores could be considered as the terrestrial analogue of the uranium-rich marine rocks.

The factors that may have controlled the relative proportion of each metal deposited are not now understood. Certainly the relative concentration of metals in the source area would be an important factor. For example, the Salt Wash sandstone, which had a single source, contains orebodies of rather uniform composition, in contrast with the Shinarump conglomerate, which had several separate sources and which contains ores of quite varied composition.

The above mechanism of origin represents a modification of views expressed by Fischer and Hilpert (11), Coffin (7), Gruner (16), Hess (18), and Webber (39) about the genesis of the uranium ores and concepts suggested by Finch (10) and others for the sedimentary copper ores. Among the facts not immediately explained by such an origin are 1) the Laramide uranium-lead ages determined for some of the uranium ore minerals, 2) the apparent association of certain districts with positive structural elements, 3) the great concentration of uranium metal in the deposits of certain districts, such as Big Indian Wash, 4) the apparent association of uranium deposits

with overlying volcanic beds. Reworking by hydrothermal solutions of uranium that was initially present within the host rocks might be consistent with all these facts.

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U. S. ATOMIC ENERGY COMMISSION,
GRAND JUNCTION, COLO.,
Nov. 21, 1954

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URANIUM ORE CONTROLS OF THE HAPPY JACK DEPOSIT WHITE CANYON, SAN JUAN COUNTY, UTAH

LEO J. MILLER

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ABSTRACT

The major uranium ore control of the Happy Jack uranium deposit of White Canyon, San Juan County, Utah, is a paleostream channel containing sediments of the Shinarump conglomerate. Intrachannel controls include organic matter, lithologic variations, and channel "lows."

Microscopic studies reveal that uraninite, the primary ore mineral, occurs as cement and as a replacement of organic material. Both uraninite and copper sulfides replace secondary quartz overgrowths. Uraninite is dated as later than the secondary overgrowths and of about the same age as the copper sulfides.

INTRODUCTION

STUDY of the Happy Jack uranium deposit was undertaken during April and May 1952, as preliminary work for a diamond drilling program carried out by the U. S. Atomic Energy Commission. The ore controls described herein were tentatively outlined by this study and have been largely confirmed by the drilling. The regional distribution and nature of the Shinarump con-

glomerate has been developed by the author and colleagues, as part of a continuing study of the White Canyon uranium deposits carried out by the Atomic Energy Commission.

The Happy Jack mine is located in the White Canyon of San Juan County, southeastern Utah, adjacent to Utah State Highway 95. Exposed formations, all of which are continental deposits, range in age from Permian through Jurassic (Fig. 1). The topography is rugged, with the crests of the canyon walls 2,500 feet above the valley floor.

White Canyon is on the west flank of the Monument upwarp, a broad structural feature locally known as the Elk Ridge anticline. The beds have a uniform strike of N 15° W and dip 1½° SW. A conjugate joint system is manifest throughout the area, with the dominant set striking N 50° E and the minor set N 55° W. Both sets have a vertical dip.

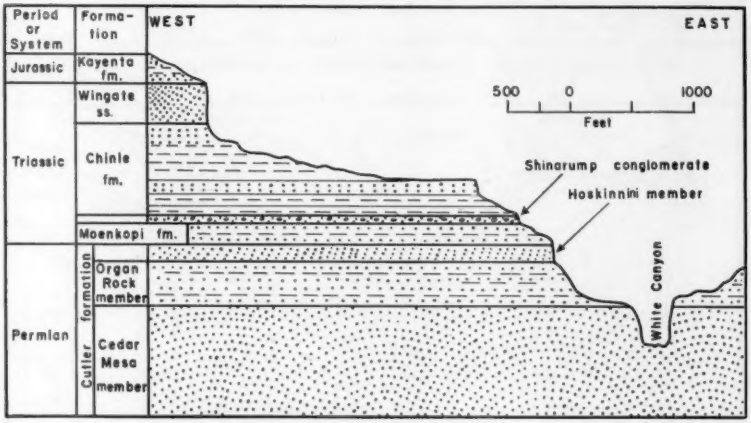

FIG. 1. Generalized section of the Happy Jack area, San Juan County, Utah.

Gregory (7) carried out the earliest reconnaissance of the region. Fischer and King (6), Smyth (14), Granger and Beroni (8), and Benson, et al. (3), have investigated the area and Dodd (4) mapped a portion of the Happy Jack mine. Bain (1) has also recorded his impression of the Happy Jack; Gruner and Gardiner (9) have written a brief account of the mineralogy.

SHINARUMP CONGLOMERATE

The Happy Jack has been the most productive among a number of uranium-copper deposits in the White Canyon area. All are in the Shinarump conglomerate of Triassic age. This formation is a lenticular sandstone that is fluvial in origin, generally conformable with the Chinle formation above, and disconformable with the Moenkopi formation below.

The distribution of the Shinarump conglomerate in the White Canyon area is suggestive of an elongate alluvial fan deposit (Fig. 2). This fan appears to have had its origin east of the Elk Ridge anticline, as evidenced by: (1) eastward increase in the proportion of pebbles in the Shinarump; (2) increase in thickness of the Shinarump to the east; (3) westerly dipping cross-bedding directions; (4) westerly channel orientations.

The Happy Jack deposit is located on the northwest "pinch-out" of the fan. The control that this feature may have on ore deposition is discussed under intra-channel ore controls.

The thickness of the Shinarump is related to the configuration of the irregular erosion surface on which it was deposited. This surface, the top of

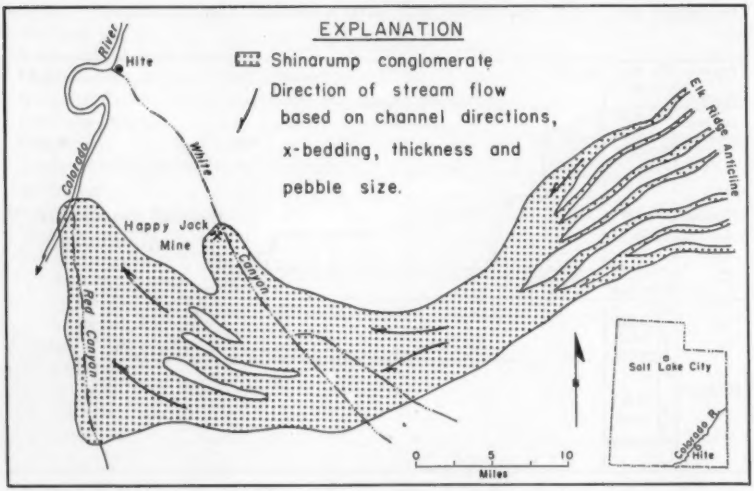

FIG. 2. Regional distribution of the Shinarump conglomerate, White Canyon, San Juan County, Utah.

the Moenkopi formation, is marked by paleo-drainage channels which are filled by Shinarump clastics. These sediments extend beyond the narrow confines of the channels and wedge-out in certain interchannel areas.

In cross section, a typical channel is an asymmetrical trough incised into the Moenkopi formation. It is 100 to 250 feet wide and 20 to 40 feet deep (Fig. 3). Along its course the undulating basal surface of a Shinarump channel may have a relief as high as 40 feet (Fig. 4). As a rule the channel maintains a relatively straight course; however, the Happy Jack channel is an exception for it changes direction abruptly in the eastern portion of the area.

On the basis of lithology, the sediments within a channel may be subdivided into three units (Fig. 3).

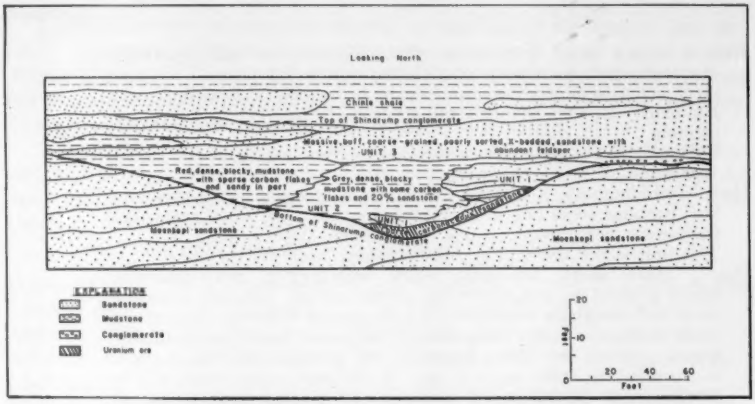

FIG. 3. Cross section A-A′, Sunrise channel, White Canyon, Utah.

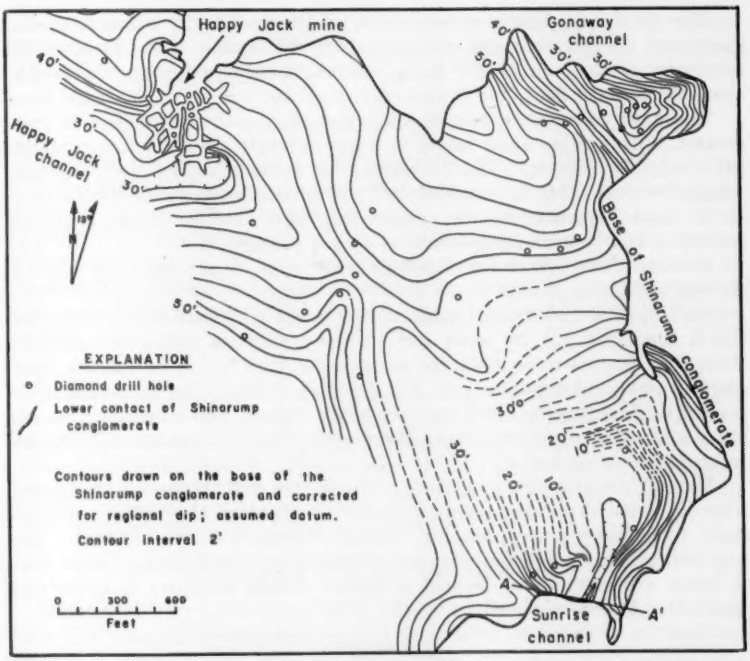

FIG. 4. Channel structure contour map of Happy Jack mine and vicinity, White Canyon, Utah.

	Thickness, feet
Unit 3 (upper unit), Sandstone, white, weathers to buff; quartzose, coarse-grained, poorly sorted, friable; grains sub-angular, clay cement, contains microcline fragments up to an inch in diameter; cross-laminated; caps the channels and occupies the intervening area; cliff-forming ..... 28 This unit is not generally ore-bearing, except locally in the Happy Jack mine.	
Unit 2 (middle unit), Mudstone, usually gray, commonly red; structureless, contains some fine to coarse sand grains; had small carbonized fragments; not present outside the channel; slope-forming ..... 12 This unit is not ore-bearing, except where near the surface.	
Unit 1 (basal unit), Sandstone, white weathers to buff; quartzose, coarse-grained to conglomeratic, poorly sorted, contains Moenkopi shale and sandstone fragments; friable, grains angular, clay cement, contains organic matter such as small twigs and ferns; predominantly quartz pebbles; few chert, quartzite and jasperoid pebbles, contains microcline fragments up to 1 inch in diameter; some chert pebbles contain fossil (crynoids and corals?); not present outside channel; slope-forming ..... 5.0 This is the ore-bearing unit.	

The basal unit, which contains most of the ore in the Shinarump conglomerate, changes character abruptly along the bottom of the channel. It commonly pinches out on the flanks of the channels and upon the "highs" along the channel floor. It is generally conglomeratic only within the lows.

The most common organic matter within the basal unit consists of compressed, broken twigs a few inches to 3 feet in length. Larger fragments are not commonly present. The Shinarump in White Canyon rarely contains silicified wood. This is a marked contrast to the abundance of this material in the same formation in other areas. Asphaltic material occurs in minute quantities and appears insignificant as an ore precipitant.

A sharp change in stream drainage and climate apparently took place at the end of Moenkopi time.

An incised cross-section testifies to the youth of Shinarump streams, and this is suggested, too, by scour and fill type sediments within the channels. After the channels were filled, the streams migrated widely within the interchannel areas and deposited unit No. 3 (Figs. 2, 3). The streams that deposited these sediments filled broad erosional valleys, and when they reached a late stage of maturity, the shales of the overlying "D" member of the Chinle formation were deposited.

Vegetal remains are extremely rare in the red Moenkopi formation, whereas in the variegated Chinle formation, carbonized plants, large silicified trees, fresh water pelecypods and Triassic vertebrates are abundant. This may indicate that conditions were more suitable for burial during Chinle time. A better explanation may be that a climatic change from dry to moist took place after Moenkopi time.

MINERALOGY

In general, the ore consists of an intergrowth of uraninite with copper sulfides, associated with minor secondary derivatives of uranium and copper.

Uraninite is the primary ore mineral of uranium in the Happy Jack deposit. Its characteristic occurrence is as replacement of wood and as cement of quartz grains. Decomposition products, the hydrated sulfates of uranium, are common at the outcrop of the ore-horizon and on the walls of the mine. The most common are johannite, zippeite, and uranopilite.

The primary ore minerals of copper are the sulfides: Chalcopyrite, chalcocite, and bornite. These, like uraninite, replace fossil wood and cement the sand grains. Secondary copper minerals include antlerite, covellite, brochantite, chalcanthite, azurite, and malachite.

The following minerals have been identified by Gruner (9):

Uraninite	Sphalerite	Covellite	Cyanotrichite
Uranopilite	Siderotil	Chalcanthite	Sulfur
Metazeunerite	Barite	Malachite	Bornite
Schoepite	Zippeite	Gersdorffite	Brochantite
Chalcopyrite	Johannite	Erythrite	Pyrite
Antlerite	Torbernite	Gypsum	Goethite
Azurite	Chalcocite	Jarosite	Ilsemannite

The textures of the Happy Jack ore are of two main types: (1) replacement and (2) exsolution. The following discussion is based on a study of 30 polished surfaces and 6 thin sections.

Replacement Textures

The most common replacement texture within the deposit is that of uraninite and chalcopyrite replacing wood cell structure (Fig. 5). Uraninite commonly replaces the cell walls and chalcopyrite occupies the central portion of the cell. The reverse situation, that of uraninite in the center and chalcopyrite in the walls of the cell, is not common. The cell border contact of uraninite and chalcopyrite is severely etched, but due to the primary structure of the wood, it is not possible to judge the time relationship between the two minerals.

Uraninite, in the absence of chalcopyrite, may completely replace the cell structure. Where this occurs the cell form is recognized with difficulty. Bornite also replaces organic matter. Some wood cells are filled with a sequence of sulfide mineral. Chalcopyrite is commonly first surrounded by chalcocite, then pyrite, chalcocite again and finally chalcopyrite. Chalcopyrite was formed first with each succeeding ring formed later.

Replacement of Quartz and Microcline

Quartz and microcline were readily etched by the ore minerals. It is not likely that some previous mineral etched the quartz, as quartz is not replaced where it is not in contact with the ore minerals. Microcline is replaced predominantly along cleavage planes (Fig. 6), but is not so susceptible to replacement as quartz.

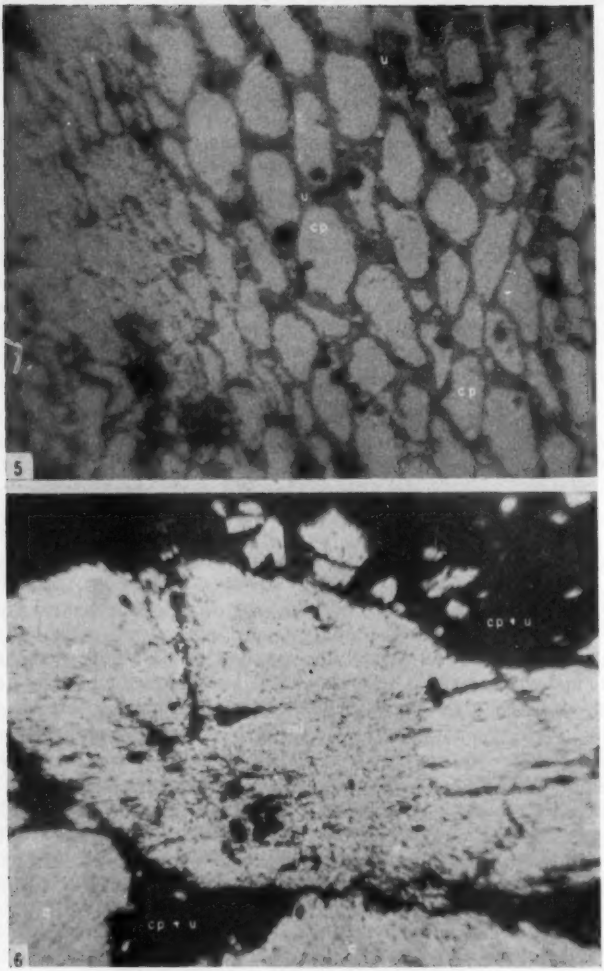

FIG. 5. Filling of wood cells by chalcopyrite (cp). Uraninite (u) surrounds the chalcopyrite and largely replaces the cell walls. 400 ×.

FIG. 6. Replacement of microcline (mi) along cleavage planes by chalcopyrite (cp) and uraninite (u). 200 ×.

Quartz overgrowths on quartz grains are common in the Shinarump conglomerate in the White Canyon area. These secondary overgrowths in specimens from the Happy Jack mine have been locally replaced by uraninite and the copper sulfides.

The clay cement is replaced more completely than quartz, though not as extensively as organic matter.

Irregular Border of Uraninite and the Copper Sulfides

The contact between uraninite and chalcocite, chalcopyrite and covellite is always irregular. This intergrowth structure does not exist between uraninite and bornite, since chalcocite, chalcopyrite or covellite is always between the two minerals. Covellite also forms alteration or reaction rims between bornite and uraninite, as reported by Rosenzweig and Gruner (9).

Fracture Filling

Uraninite has not been observed within fractures except where it follows probable shrinkage cracks in chalcopyrite. Chalcopyrite rarely follows cracks in quartz grains or replaces mudstone and well cemented sandstone along fractures.

Covellite follows fractures in chalcopyrite, bornite, chalcocite and uraninite.

Exsolution

Chalcopyrite and bornite, where found together, are always in a grating pattern, bornite being the included mineral (Fig. 7). This is apparently an exsolution texture, as described by Schwartz (13), Edwards (5), and Bastin (2). The texture has the following exsolution features: (1) chalcopyrite blade-like inclusions with no enlargement where the blades cross or join, (2) the boundaries of the inclusions are sharp, (3) bornite, the included mineral, is absent outside the intergrowths and occurs as disconnected units inside the intergrowth area.

Schwartz (13) induced this texture in chalcopyrite-bornite ore from Globe, Arizona, by artificial heating and quenching at a minimum temperature of 475° C. The significance of this temperature is uncertain as this was primarily a heating experiment. Pressure and the chemistry of the Happy Jack ore solutions may well have had a temperature lowering effect for the precipitation of uranium oxide.

Time Relationship Between Minerals

The intergrowth of minerals and the replacement and exsolution relationships indicate that there is no orderly sequence of mineralization for the ore minerals. Certainly the ore minerals are later than the quartz cement and quartz overgrowths, and covellite is later than any of the ore minerals. There is a suggestion that uraninite may be later than chalcopyrite, bornite, and

chalcocite as there are some cross-cutting relationships and uraninite in many cases encloses chalcopyrite.

The lack of a clear time sequence of mineral growth suggests a simultaneous deposition of the ore minerals.

Alteration

No significant alteration has been noted in the Happy Jack deposit. The lack of argillization and sericitization of the feldspars is conspicuous, as is the absence of calcium carbonate and silicification (excluding secondary quartz growth). The red coloration, which is common to hydrothermal uraninite deposits in North America (10), is lacking.

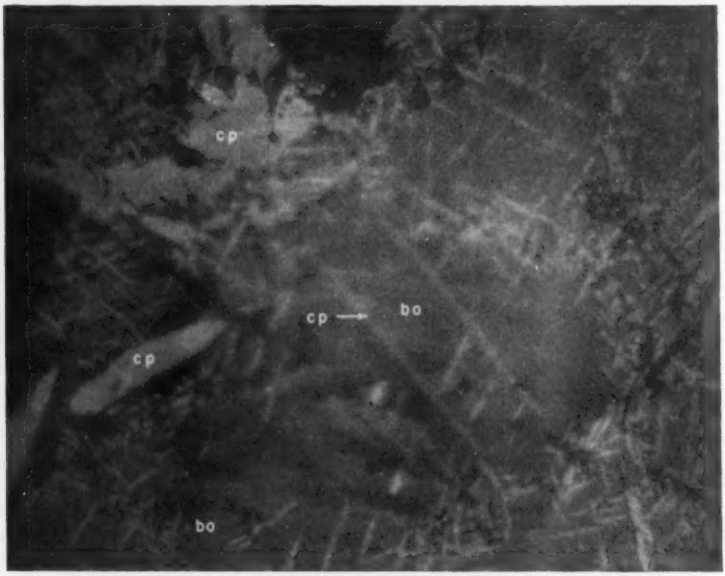

FIG. 7. Exsolution texture of chalcopyrite (cp) and bornite (bo). 1940 ×.

INTRA-CHANNEL ORE CONTROLS

All of the uranium ore in the White Canyon area is confined to Shinarump-filled paleostream channels. Some of these channels have been traced for 15 miles, but the ore bodies within them are not continuous. There must be intra-channel features that control ore deposition and produce deposits such as the Happy Jack. It is believed that the local sedimentation environment of the Happy Jack area produces intra-channel features favorable for ore deposition.

Organic Matter

In the Shinarump conglomerates, carbonaceous debris is readily seen but is very difficult to map by quantitative methods. An examination of drift walls in the Happy Jack mine (Fig. 8, DD′, HH′, NN′, PP′) reveals an abundance of carbonaceous plant debris (ferns, twigs, and logs) within the ore shoots. A small amount of low rank coal is also present. All of the sandstones associated with ore bodies have a high percentage of organic matter, which is in part or completely replaced by uranium and copper sulfides.

All organic material is not associated with an ore body. It is certain, however, that carbonized wood tissue and other carbonaceous fragments are concentrated in the ore shoots. In this region concentrations of carbonaceous material have served as leads in ore-finding.

Lithologic Controls

The Happy Jack channel deposit is unique among the channel deposits in the White Canyon area; intertonguing of sandstone and mudstone on a large scale produced favorable traps for the deposition of ore. Scour and fill sedimentation created a large number of bedding planes that were channelways for solutions. Where conditions of impermeability exist, as in tightly cemented sandstones and mudstones, there is no ore (Fig. 8, QQ′). The lithologic controls considered here are: (1) bedding planes, (2) petrological traps, (3) intra-channel scours, and (4) basal Shinarump mudstone.

Bedding Planes.—Ore is distributed in large quantities along bedding planes. It takes the form of massive tabular uraninite as much as two inches thick, and bands of disseminated uraninite ranging in thickness from one to twelve inches. The copper sulfides form massive laminae up to 3 inches thick and also form disseminations throughout the sandstone bed.

Specimens taken from bedding planes display some cell structure, indicating that here, too, organic matter played an important role in the precipitation of ore.

Bedding plane ore shoots can be traced for short distances (Fig. 8, DD′); however, an attempt to correlate these planes from drill hole logs has proven unsuccessful.

Petrologic Traps.—An interesting and local phenomena in the Happy Jack channel is the presence of high-grade ore in porous carbonaceous sandstone that is a wedge in an impervious mudstone (Fig. 8, HH′). These ore shoots appear to have no relationship to the present regional dip. This circumstance may be an indication of movement of ore solution under pressure that involved either artesian circulation of ground water or hypogene solutions.

Intra-channel Scours.—Scours into the Shinarump mudstone are filled with a coarse carbonaceous sandstone, unit 1, which in many places carries high-grade uranium mineralization (Fig. 8, GG′). It is possible to correlate this feature for distances through the deposit by the aid of a fence diagram (Fig. 9). The porous sandstone within the scour may have acted as conduit for the ore solutions.

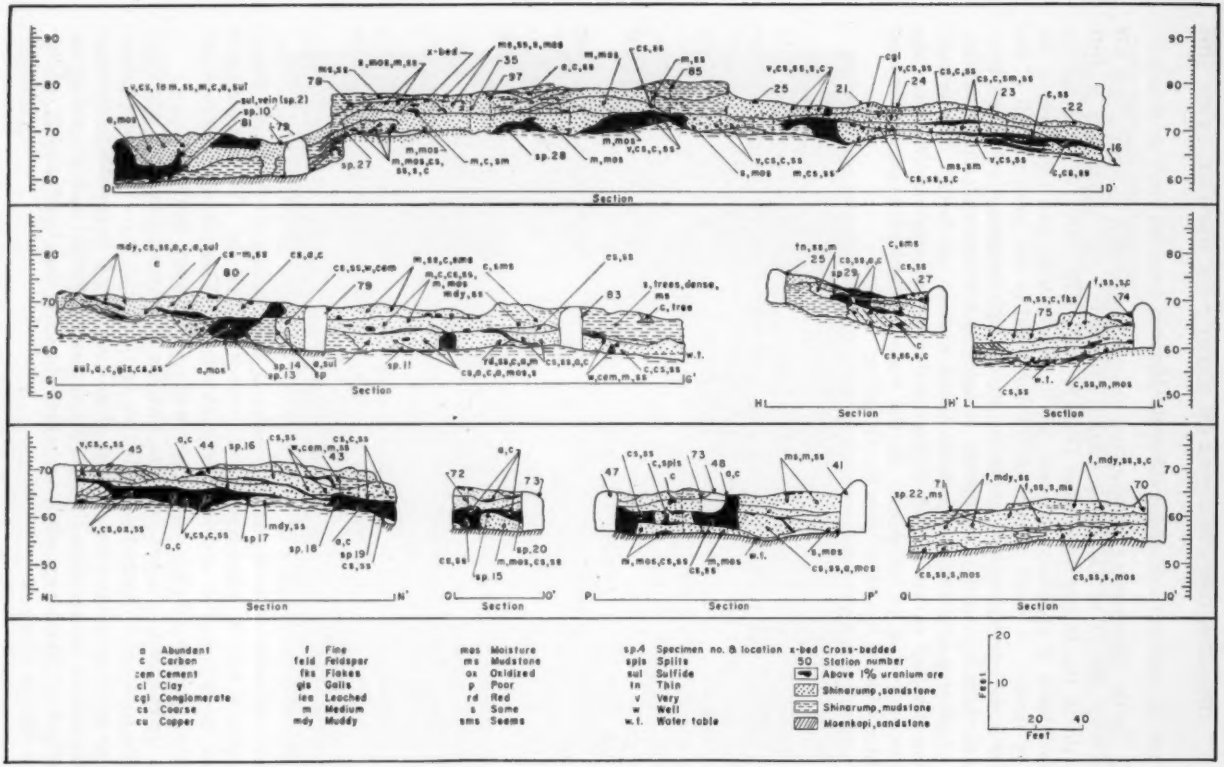

FIG. 8. Cross sections of Happy Jack mine, White Canyon, Utah.

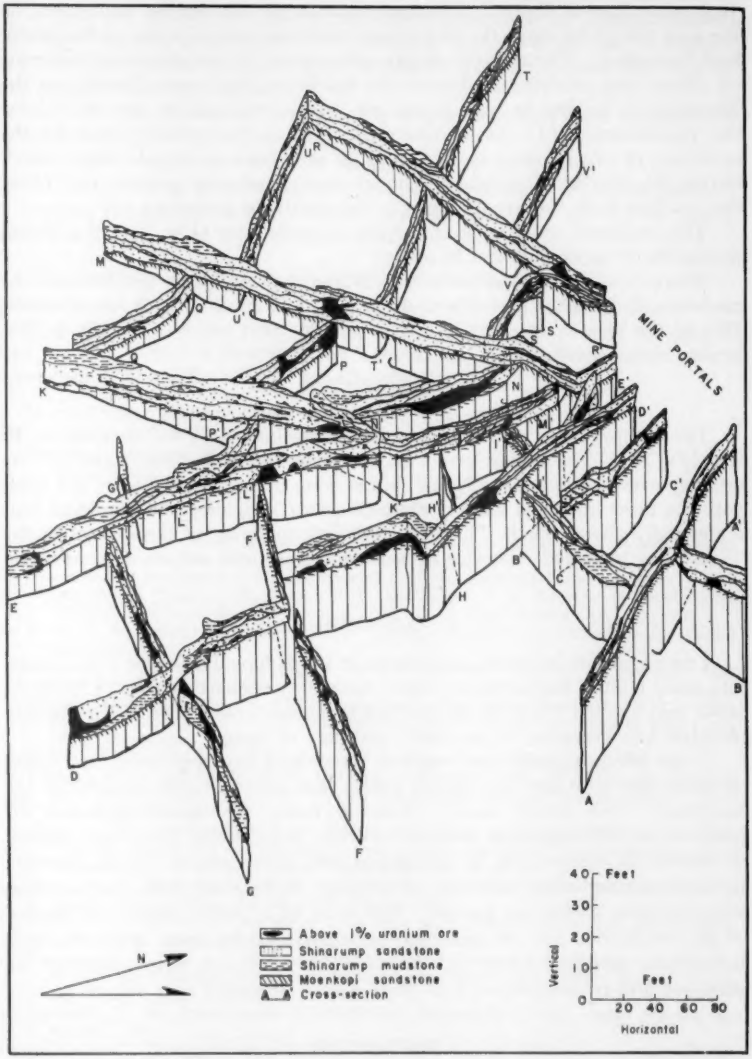

FIG. 9. Fence diagram, Happy Jack Mine, White Canyon, Utah.

Basal Shinarump Mudstone.—The workings on the east side of the Happy Jack mine have a floor of Shinarump mudstone overlain by sandstone; on the west side of the mine, the Shinarump sandstone rests directly on the Moenkopi formation. The rich ore shoots are confined to the sandstone that rests on Shinarump mudstone, whereas the sandstone that rests directly on the Moenkopi is lacking in high grade ore. Two explanations are offered for this phenomenon: (1) the mudstone provided an impermeable floor for the solutions; or (2) the mudstone contains an abundance of organic flakes, which during the petrification produced enough uranyl reducing gases to precipitate the uranium from the ore solutions in the overlying sandstone.

This mudstone unit can be traced for some distance (Fig. 9) and a logical prediction of its location can be made.

There is a strong possibility that Shinarump sandstone lies beneath the mudstone floor on the east side of the Happy Jack mine (Fig. 8, cross section DD′ in the vicinity of sp. 27). It is possible that more ore exists in this locality under the floor.

Channel Lows

The Happy Jack channel system has intra-channel "lows" as deep as 40 feet (Fig. 4). The richest ore in each channel is within these "lows." The ore may persist between the "lows" but is quite thin. These "lows" are filled with the three lithologic units of the Shinarump conglomerate; the basal unit is generally absent on the "highs." The intertonguing of these units in the "lows" has produced favorable sedimentary structures for the concentration of ore.

FRACTURES

Three types of fractures are present in the Happy Jack mine: (1) joints, (2) small faults (displacement 1-foot) caused by regional tension, (3) minor faults that are the result of pene-contemporaneous compaction. No primary uranium mineralization is associated with any of these.

It has been suggested that regional stress may have produced local zones of shear that fractured the quartz grains and increased the porosity of the sandstone. This theory has no relation to facts. The quartz grains in the primary ore at Happy Jack show no uranium in fractures; they show instead an interstitial replacement of the grains and their cement. It is common, however, for secondary minerals of uranium to lie along joint surfaces and even fractures within the grains. This is to be expected where the erosion of the overburden has released rock pressure, allowing open spaces to form both in the sandstone units and quartz grains. Ground water dissolves the uraninite and re-precipitates it in open spaces, generally as a sulfate.

CONCLUSIONS

Several controls of uranium deposition in the Happy Jack deposit appear to be demonstrated by substantial evidence:

1. All of the uranium ore is confined to a Shinarump stream channel.
2. The ore within the channel is largely controlled by organic matter, lithologic features, and channel lows. Most of these controls can be mapped and with their aid favorable ore-ground may be predicted beyond the outcrop, and beyond the mine heading.
3. Structural features of tectonic origin appear to have been unimportant in the localizing of ore bodies.
4. There is no alteration of the minerals within the deposit.
5. The ore, from evidence gathered, is not the result of detrital deposition. It replaces the cement of the sandstone and the secondary growth on quartz grains, and must have formed from circulating solutions.

The writer is grateful to Frank Frankovich and John Masters, A.E.C. geologists, for their help in field mapping and to Robert J. Wright for his aid in the preparation of this report. The cordiality and assistance of the Happy Jack owners, Fletcher Bronson, Joe Cooper, and Grant Bronson, and mine supervisor Warren Bronson, is greatly appreciated.

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URANIUM ORE GUIDES, MONUMENT VALLEY DISTRICT, ARIZONA

THOMAS W. MITCHAM AND CHARLES G. EVENSEN

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ABSTRACT

The contact between the Shinarump conglomerate and the Moenkopi formation, both of Triassic age, is a marked erosional unconformity. Basal Shinarump sediments fill ancient stream channels incised into the underlying Moenkopi. On the Colorado Plateau uranium ore deposits are commonly found in these stream channels. Paleostream channels are the prime guide to ore in the Shinarump. Twenty-seven others of varying degrees of usefulness are summarized.

INTRODUCTION

Search for ore is the search for and the application of significant spatial relationships between orebodies and various geologic features, i.e., ore guides.

Objectives of this paper are the listing of new ore guide concepts, and the compilation of previously described ore guides for uranium deposits of Monument Valley. Undoubtedly, a number of these guides apply to Shinarump ore deposits elsewhere on the Colorado Plateau.

GEOLOGIC SETTING

Monument Valley is on the Navajo Indian Reservation and lies on the Arizona-Utah state line south of the San Juan River (Fig. 1), at the southern end of the Laramide (?) Monument upwarp, one of the largest and most prominent structural features of the Colorado Plateau (6, 7). North-trending folds within the upwarp are rather common. Pliocene volcanic necks and dikes of minette tuff-breccias, which tend to follow strong fracture systems, are common (6, 11). The most prominent structural features are

Comb Ridge, which forms the southeast boundary of the Monument upwarp, and the north-trending Organ Rock anticline that lies a few miles west of the Oljetoh channel.

From Pennsylvanian through Cretaceous time, according to Baker (2), over 7,000 feet of sediments, mostly of continental origin, have accumulated in the Monument Valley area. Only that part of the stratigraphic section directly related to Shinarump ore deposits is described in this paper.

The massive eolian DeChelly sandstone is a member of the Permian Cutler formation. The DeChelly sandstone forms the picturesque spires, buttes, and mesas for which Monument Valley is famous. In some areas, this is overlain by the Hoskinnini tongue (?) of the same formation, a red-brown sandy mudstone as thick as 88 feet.

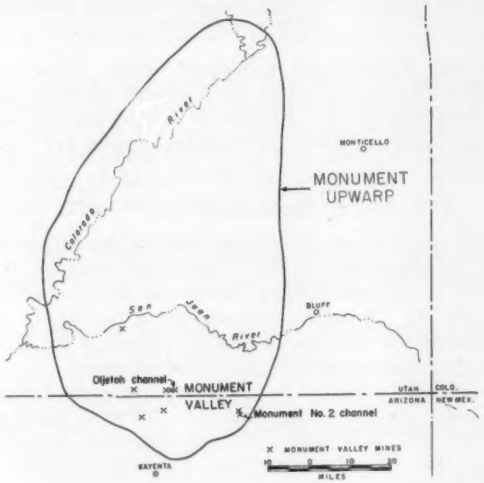

FIG. 1.

The Lower and Middle Triassic Moenkopi formation lies on the Cutler formation. The Moenkopi formation consists of red-brown siltstone and mudstone with some sandstone beds. It varies in thickness up to 340 feet, and is absent in some localities. After Moenkopi deposition, stream channels were deeply incised into it, and in some areas this erosion cut through the Moenkopi, Hoskinnini and into the DeChelly sandstone. Basal Shinarump sediments later filled these channels.

The Shinarump conglomerate is a basal member of the Upper Triassic Chinle formation. It varies in thickness up to 350 feet, and is absent in some areas. The product of a fluvial environment, it consists of lenses of coarse-grained sandstone, conglomerate, and mudstone (Fig. 2). It also

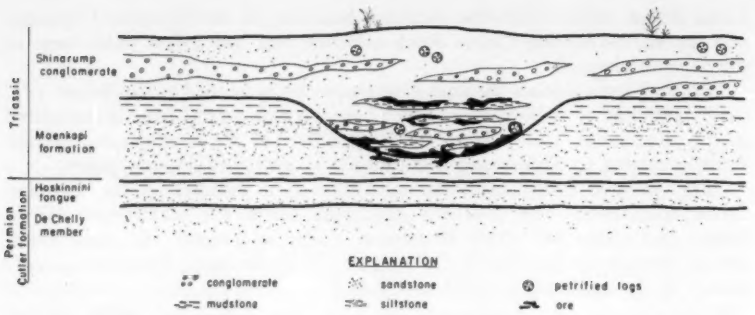

FIG. 2. Schematic cross section of a typical ore-bearing Shinarump channel in Monument Valley.

contains abundant silicified and carbonized wood. The overlying Chinle consists of 790 to 960 feet of mostly multi-colored siltstones and mudstones. Because the Shinarump is quite resistant to erosion and the overlying Chinle is easily eroded, buttes and mesas in Monument Valley are commonly capped by Shinarump.

MINERALIZATION

Gregory (6) noted copper and copper-uranium deposits in the Shinarump conglomerate of Monument Valley. Significant uranium orebodies have been found only in Shinarump-filled channels at the base of the Shinarump conglomerate (9, 10). A considerable amount of ore has also been extracted immediately beneath the floor of Shinarump channels in the Moenkopi formation and in the DeChelly member of the Cutler formation.

Various vanadium, copper, and uranium minerals replace carbonized and silicified wood, and cementing material. Minerals associated with ores are both primary and secondary. Minerals identified include chalcopyrite, chalcocite, uraninite, roscoelite, hewettite, gummite, carnotite, tyuyamunite, malachite, azurite, chrysocolla, limonite, jarosite, alunite, gypsum, and barite (6, 8).

Ore has been extracted from a number of mines in Monument Valley. The Monument No. 2 mine of the Vanadium Corporation of America has been the largest uranium producer.

Replacement phenomena and the spotted distribution of orebodies lead the writers to conclude that the orebodies are epigenetic. The nature and source of the mineralizing solutions and the various ions they carried are in dispute, and no acceptable explanation has been proposed.

SHINARUMP ORE GUIDES

Erosion has completely removed the relatively soft Chinle beds from large areas on mesa surfaces in the Monument Valley area, leaving many square miles capped by Shinarump conglomerate. Criteria by which the

significance of Shinarump channel outcrops can be assessed are important. Of particular importance, however, and certainly more challenging, are criteria that will allow, by a study of cappings of the upper Shinarump on mesas, the detection of Shinarump channels, scours along them, and ore within them.

A number of guides for Shinarump uranium ore in Monument Valley have been described. The twenty-seven possible ore guides listed below consist of fourteen new concepts and a compilation of thirteen that have been described by others. Only a few of the guides are well established. Guides suggested by the writers require further evaluation and many of the other guides require re-evaluation.

The twenty-seven guides are listed according to an outline based on five probable genetic categories.

Sedimentary Structure.—1. Orebodies tend to occur at the base, low on the flanks, and at the top of basal Shinarump channels (9) as shown in Figure 2.

2. Channels floored by sandstone are favorable for large orebodies (9). The Monument No. 2 channel transects the Moenkopi, the Hoskinnini, and the upper part of the DeChelly. All of these formations contain sandstone beds, any one of which may serve as a favorable channel floor.

3. Channel widths of 300 to 1,000 feet are more favorable than are broad channels.[1] Some Shinarump channels of Monument Valley are as broad as 2,300 feet (13).

4. Channel "deeps"—scours below the average floor of the paleostream channel—according to Chester (3) are favorable for localization of large orebodies.

5. Meander bends are favorable for ore localization—on meander bends (3) or just downstream from meander bends (1).

6. Permeability trends should be guides to mineralization trends. In a formation so permeable as the Shinarump, ore solutions must have moved laterally to some extent. Thus, an index to permeability should be a guide to the path of mineralizing solutions.

7. Loci of rapid facies changes from sandstone to mudstone should be favorable for ore localization. This phenomenon is commonly associated with uranium deposits in the Morrison formation on the Colorado Plateau. Baker (2) described a locality in Monument Valley where a Shinarump section, 100 feet thick, changes entirely from sandstone to mudstone within a lateral distance of 1,000 feet.

8. A lithologic complex of mudstone boulders and pebbles in sandstone, according to Witkind (13), is favorable for ore localization. From observations in other uranium deposits on the Plateau, it seems that mudstone-sandstone interfaces tend to be loci intense in mineralization. Interfaces are abundant in mud-pellet and mud-chip conglomerate zones.

9. Conglomerate lenses between beds of cross-bedded sandstone appear to be especially favorable. Conglomerate lenses are elongated parallel to channel trends (13).

[1] Personal communication from John F. Hill, Geologist, Sheridan-Wyoming Coal Company.

10. Ratio of mudstone to sandstone in a channel is probably significant. Optimum ratio may be 1 : 1, which would result in abundant interfaces if the different lithologic types are interbedded, and yet both ratio and bedding would allow sufficient permeability for passage of mineralizing solutions (Fig. 2).

11. James D. Lowell [2] has suggested that log concentrations in the upper part of the Shinarump may result in precipitation of ore in the lower Shinarump channel fill. Organic material, leached from logs by ground water moving downward, may have precipitated ore minerals from "perched" solutions moving laterally along channel floors.

12. Upstream channel fillings are more favorable than downstream fillings that tend to be excessive in mudstone (1). Shinarump streams flowed northwesterly across Monument Valley.

13. Orebodies are most likely to be found upstream from mud deltas. Bain (1) suggested that such deltas formed at the confluence of streams, the deposits from one stream blocking further movement of uranium-bearing detritus. This, of course, assumes a syngenetic origin.

Diagenetic Structure.—14. Surfaces of Shinarump-capped mesas may show reverse topographic reflections of basal channels and scours within them, due to differential compaction (Fig. 2). If Moenkopi muds were yet unconsolidated at the end of Shinarump time, then compaction of channel banks would exceed that in channels because of thicker mud on the banks. This would have resulted in lowering of the Shinarump over banks relative to that over channels.

Topographic studies of mesa surfaces should be undertaken to test this concept, but reverse reflections of channels may not be revealed for three reasons: (1) Moenkopi muds may have been indurated prior to Shinarump deposition; (2) facies changes in the upper Shinarump and lower Chinle may conceal such phenomenon; (3) such topographic expressions on mesa cappings may be much marred or erased by recent erosion.

Tectonic Structure.—15. As a stress-resisting unit, the Shinarump conglomerate can be considered as a relatively brittle "thin sheet." On the underside of the formation are scattered inverted ridges which are casts of ancient stream channels generally incised into the Moenkopi formation. These ridges can be considered as thin-sheet stiffeners. Both the underlying Moenkopi and the overlying Chinle formation contain considerably more mudstone than the Shinarump, and as rock bodies, they behave more plastically under regional stress. Thus, the brittle Shinarump thin sheet is in effect mounted in a plastic medium.

Under horizontal regional stress, strain behavior of the Shinarump thin sheet should differ in the thicker channel areas from its behavior in thinner areas. This should result in a changed fracture pattern in the vicinity of channels. Thus, study of fractures over large Shinarump-capped areas might well allow one to detect positions of channels and scours within them. A preliminary survey indicates: (1) a relative paucity of fracturing over

[2] James D. Lowell, Geologist, U. S. Atomic Energy Commission, personal communication.

channels; (2) that regional tension fractures tend to change strike in the vicinity of channels to a bearing that is more nearly normal to channel axes.

16. Some fractures are apparently pre-ore and may have controlled ore deposition.

17. The lower portions of limbs of anticlines and monoclines are more likely to contain ore deposits than higher portions (1).

18. Orebodies may bear significant spatial relationships to Pliocene volcanic intrusives. Most large orebodies found in Monument Valley have been in the Oljetoh and Monument No. 2 channels. The Oljetoh channel and possibly the Monument No. 2 channel are intersected by dikes. Chester (3) states that some intrusives of the area are abnormally high in uranium.

Mineral Distribution—Cause or Effect of Ore Emplacement.—19. Subtle color differences, due to alteration in the upper Shinarump above large orebodies, may be expected. Commonly, the Shinarump is less than 100 feet in thickness. It is logical to assume that the rather intense chemical activity which took place during emplacement of a large orebody, would have altered rocks surrounding it for at least a few tens of feet.

20. Variations in color and volume of bleached Moenkopi in channel floors may be significant. It has been observed that colors of such bleached rocks are shades of yellow, green, cream, and light gray. Bleached Moenkopi zones range from a fraction of an inch to eight feet in thickness.

21. The presence and/or variations in abundance of carbon, copper, manganese, and limonite in channels may be significant, according to Cummings (4), Bain (1), and Gregg (5). Eleven outcrops of anomalous radioactivity were checked: 11 contained limonite and manganese; 4 contained carbon and copper (4).

22. Color and texture of limonite might well be significant; these are commonly of critical importance in copper exploration.

23. Variations in clay minerals of mudstones due to alteration by uranium-bearing solutions may be significant.

24. According to Bain (1), jasperoid pebbles in channels are quite significant. He states: "The uraninite capacity of the jasperoid has been identified . . . jasperoid and comminuted jasperoid" (is identified) "as the carrier of primeval uranium in the Shinarump beds."

25. Subtle radioactivity highs might be expected over large orebodies on Shinarump-capped mesas. This could be due to halos of ions formed at the time of ore emplacement, to upward diffusion in ground water, or to the leakage of radon gas through fractures.

Supergene Activity.—26. Subsidence over oxidized orebodies, due to volume decrease resulting from leaching, is a possibility.

27. Deposits tend to become enriched down dip in advance of erosion (Bain, 1).

U. S. Atomic Energy Commission,
Grand Junction, Colo.,
Nov. 23, 1954

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APPLICATIONS OF CROSS-STRATIFICATION STUDIES TO PROBLEMS OF URANIUM EXPLORATION, CHUSKA MOUNTAINS, ARIZONA

JAMES D. LOWELL

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ABSTRACT

Ancient stream directions in the lower Morrison formation of the Chuska Mountains, Arizona, may be reconstructed through use of cross-stratification mapping techniques. Dip directions of the cross-strata, when combined in the forms of histograms and vector resultants, indicate directions of paleostream flow. This latter is the direction of maximum porosity and hence the direction along which uranium orebodies and the bleached zones that surround them are most likely to be found. Plotting of the sedimentation structural features defines intersections of ancient stream systems, and these localities appear to be favorable loci for deposition of uranium ore. A possible relation between type of stratification and location of uranium orebodies is described.

INTRODUCTION AND ACKNOWLEDGMENTS

CROSS-STRATIFICATION, asymmetrical ripple marks, and lineation (the alignment of clastic particles) (5) indicate the direction of flow of an ancient aggrading current. Experience suggests that there is a relationship between direction of ancient sedimentary trends and the orientation of uranium orebodies.

The writer wishes to acknowledge the help of E. D. McKee and W. L. Stokes who read and criticized this paper. Former studies of the Morrison formation by the latter were the inspiration for this paper.

R. L. Rock and J. A. Masters collected much of the field data used in this report and made many helpful suggestions.

LITHOLOGY AND STRATIGRAPHY

The features discussed in this paper occur in a 5-mile square area near the northern termination of the Chuska Mountains, Arizona (Fig. 1). The

sedimentary units involved comprise the uranium-bearing zone in the lower 100 feet of the Morrison formation. This stratigraphic zone is composed of alternating, discontinuous beds of mudstone and sandstone. Sandstone beds, from a few inches to 50 feet thick, make up approximately 60 percent of the unit. The mudstone beds range from less than an inch to 10 feet in thickness. Mud-pellet conglomerate beds are numerous and vary from one to five inches in thickness.

The sandstone of the lower Morrison consists of fine to very fine quartz grains generally stained red, but including sandstone ranging from tan to gray. Sorting is fair and no grains larger than "fine" (Wentworth scale) are found in the mineralized zone. The mudstone varies from red to dark gray.

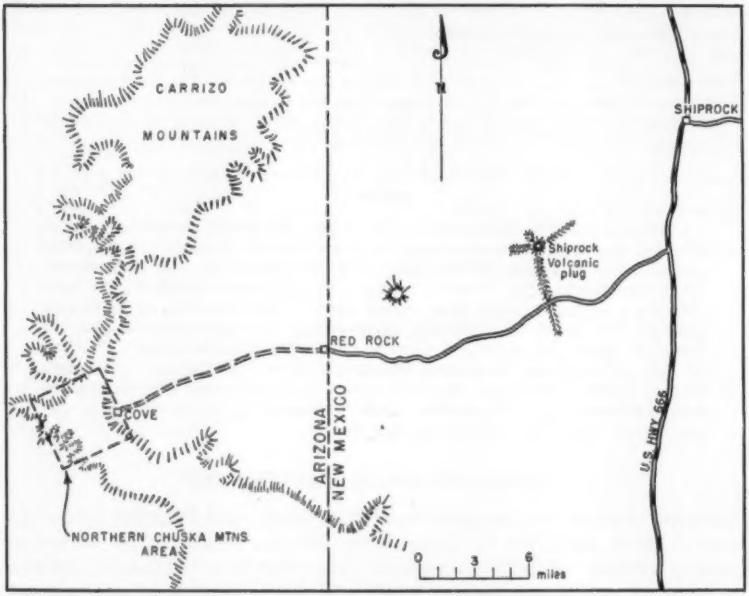

FIG. 1. Location map of Northern Chuska Mountains area, Arizona.

The area covered by this report is on the extreme southern edge of a stream-laid fan of sediments, the Salt Wash member of the Morrison formation. Craig (1) describes this locality as one in which the Recapture member of the Morrison formation interfingers with the Salt Wash member. South of the area, Recapture beds occupy a stratigraphic position equivalent to that of the Salt Wash within the area. The writer believes that the junctions of northeast-trending streams depositing the Recapture sediments, and southeast-trending streams that deposited the Salt Wash sediments, are apparent in the cross-stratification of the area.

The interrelation between directional trends of sedimentation and uranium mineralization is based on this working hypothesis: uranium was carried in solutions that traveled through the sediments that fill a complex of ancient stream channels comprising a porous and favorable lithologic environment (Fig. 2). Ore minerals were precipitated in those paleostream channels by carbonaceous material and/or by favorable permeability. The uranium is, in most occurrences, associated with vanadium in carnotite.

FIELD METHODS

Cross-strata dip directions, asymmetrical ripples, and lineation were mapped only in those sandstone zones, generally 10 to 50 feet thick, of the lower Morrison that contain uranium-bearing minerals. Where two or more

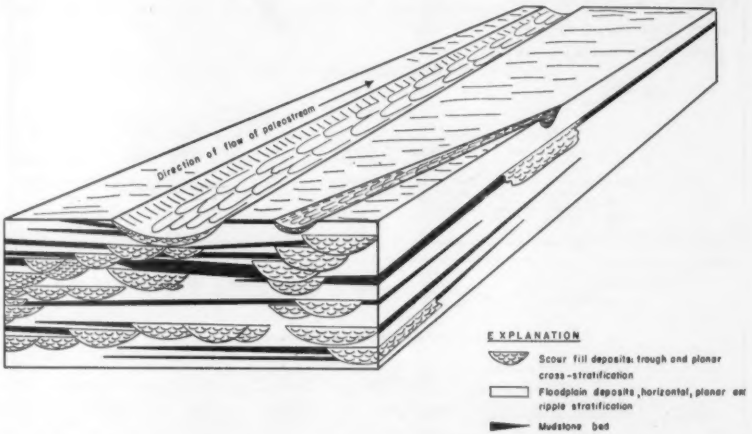
Direction of flow of paleostream
EXPLANATION
Scour fill deposits: trough and planar cross-stratification
Floodplain deposits, horizontal, planar or ripple stratification
Mudstone bed

FIG. 2. Schematic diagram showing deposition by a typical lower Morrison stream in the Northern Chuska Mountains area, Arizona.

mineralized zones are separated by several feet of barren material, separate mapping was done on each of the ore horizons. Directions of sedimentary features were not corrected for regional dip, which averages only 1½ degrees. Dips of less than 5° were not recorded because low dips are inconsistent in direction.

The nomenclature of cross-stratification used in this paper is that proposed by McKee and Weir (5). Table 1, adapted from those authors, describes the types of cross-stratification.

Directions of dip were taken on sets or fragments of sets of cross-strata. Whole sets of trough cross-stratification have a greater consistency in dip direction than other types and are given double weight in the calculations.

DISCUSSION OF DATA

There is no evidence to suggest that in any specific area the ore solutions traveled through a single, ancient stream scour in a mineralized region; rather, they percolated through a network of overlapping channels—the

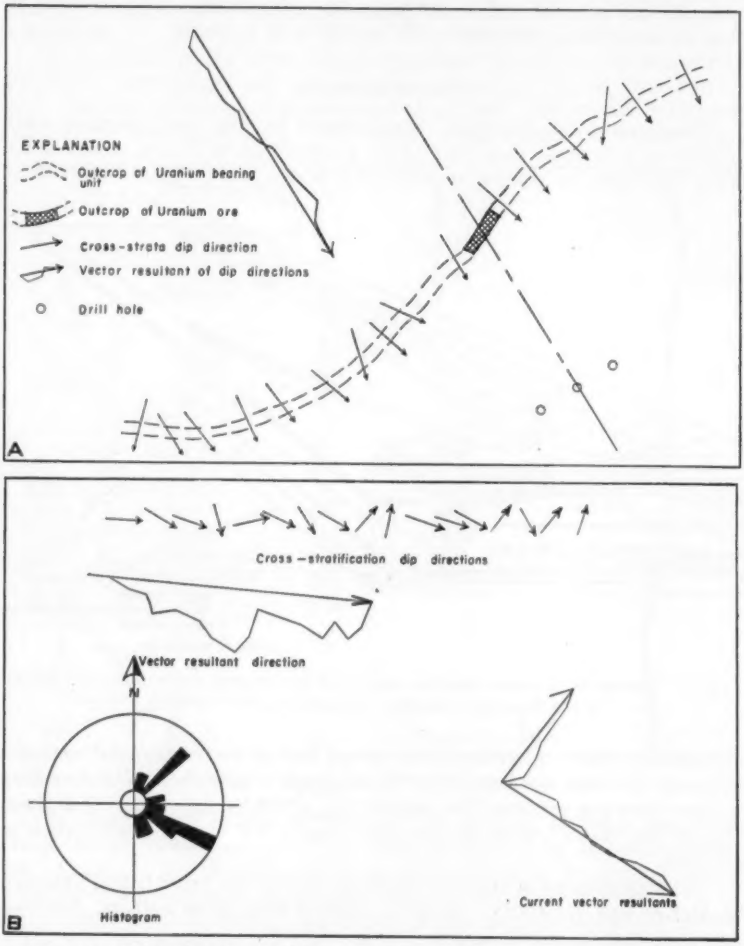

FIG. 3A. Method of projection of uranium orebodies along cross-strata dip direction trends.

FIG. 3B. Analysis of a typical group of cross-stratification dip directions from the Mesa 4½ area, Apache County, Arizona.

optimum paths of maximum permeability. Therefore, groups of cross-stratification directions, each of which indicates a local direction of paleostream flow, have greater significance than individual directions in projection of paleostream flow—the path of greatest permeability, and hence uranium ore trends. A method of grouping cross-strata dip directions is also useful in determining, on the regional scale, patterns of ancient stream flow.

Directions of paleostream flow, shown by cross-stratification, are plotted by arrows, each of which represents an average of three cross-strata dip directions. These arrows plotted on the field maps have been collected into groups and replotted as vectors (Fig. 3-A), which combine into a single average direction the irregular line formed when the short arrows are plotted end to-end, each on their correct azimuth. This method is used in preference to a method which combines directions trigonometrically because the vectors more readily illustrate the grouping of the readings into distinct "currents."

TABLE I. - DESCRIPTION OF CROSS-STRATIFICATION TYPES USED IN THIS REPORT

TYPE	LONGITUDINAL SECTION	CROSS SECTION	SHAPE OF LOWER BOUNDING SURFACE	SHAPE OF SET IN CROSS-SECTION	GRAIN SIZE	REMARKS
SYMMETRICAL TROUGH "FESTOON TYPE"			CONCAVE SCOUR SURFACE	SYMMETRICAL LENTICULAR	FINE-VERY FINE	AXIS PLUNGES 5 - 20°
ASSYMMETRICAL TROUGH			CONCAVE SCOUR SURFACE	ASSYMMETRICAL CONCAVE UPWARD	FINE WITH OCCASIONAL MUD BALL CONGLOMERATE	THIS GRADES INTO THE SYMMETRICAL TROUGH AND WEDGE TYPES
PLANAR "HELICAL" OR "DIAGONAL" TYPE			HORIZONTAL SURFACE OF NON-DEPOSITION	PARALLEL SYMMETRICAL	FINE-VERY FINE	USUALLY OCCUR AS ALTERNATING HORIZONTAL AND CROSS-STRATIFIED SETS
WEDGE "CUT-AND-FILL" TYPE			INCLINED PLANAR TO CONCAVE UPWARD, IRREGULAR	WEDGE SHAPED	FINE WITH ABUNDANT MUD CALL CONGLOMERATE	COARSEST GRAINS AND WIDEST DIVERSION OF DIRECTIONS OF INCLINATION OCCUR IN WEDGE CROSS-STRATA

RIPPLE CLASSIFICATION

TYPE	PLAN	LONGITUDINAL SECTION	AVERAGE INDEX	REMARKS
CURRENT ASYMMETRICAL WITH ROUNDED CRESTS			17	PSEUDO-CROSS-LAMINATION IS VERY COMMON AND HAS LED TO MANY ANOMALOUS DIRECTION READINGS. PSEUDO STRATA (STOSS-SIDE SURFACES) ARE 1 - 5 INCHES APART.

Following the practice of Reiche (7), the most divergent arrows are eliminated from the calculation of resultants. Decision as to what constitutes a divergent arrow is based on a histogram plotting of each group of directions. In some cases, divergent directions fall into two groups consistent in directions (Fig. 3-B). In this figure, the two groupings shown by the histogram are plotted separately as current vector resultants.

Individual trough cross-strata occur as concave-upward trough-like surfaces plunging in the direction of the current (4), Table 1. Directions of dip measured on opposite sides of trough cross-strata diverge in direction as much as 70 degrees (Fig. 4-A). This fact was considered in evaluations of the consistency of groups of dip directions.

In many localities, a few cross-strata dip readings show directions reversed 180° from the average of the area. This can be seen in the histogram

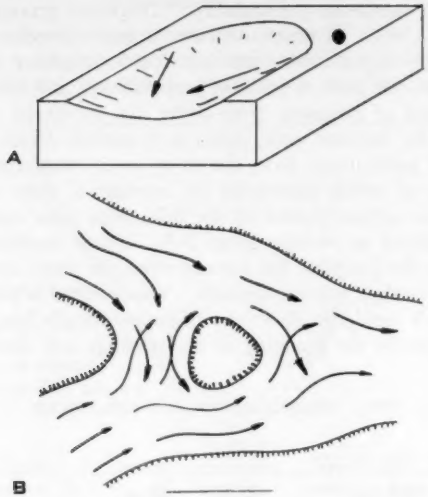

FIG. 4A. Sketch showing divergent directions of dip on opposite sides of a trough cross section.

FIG. 4B. Sketch showing confluence of streams and areas where current directions reverse during floods.

for the northeast side of Three Point Mesa (Fig. 5). For purposes of projecting orebodies along current directions, it is not important to differentiate upstream and downstream, but other applications make a correct choice between the two desirable. Readings reversed 180° from the expected direction may be due to pseudo-cross-stratification (6). Many pseudo-cross-strata are conspicuous, whereas individual ripple surfaces are not. The apparent stratification will, in such cases, appear to be planar. Many anomalous readings are obviously due to trough cross-stratification. Reversed trough cross-strata may be explained by alternating directions of flow through channels at the confluence of streams at times of flood (Fig. 4-B). A correct interpretation of the direction of movement of sediments in both of the situations described above would require reversing the anomalous direction. For that reason when two current directions reversed 180° are plotted in the histogram, the current direction having the fewest number of readings is assumed to be anomalous and those readings are eliminated. In cases not involving reversed readings, a maximum of 10 percent of the most erratic readings are eliminated as in Reiche's work (7).

In the majority of the several mineralized areas mapped in detail, there is a similarity in pattern of diverging current directions around the orebodies. This repeated pattern is always at the junction of two consistent currents (Fig. 5). This intersection of current directions appears to have produced

an increase of turbulence in the ancient streams with a consequent difference in material deposited. This change resulted in a modification in the turbulent area of the type of cross-stratification and locally an increased percentage of sandstone over mudstone and in the development of diagonal mud bars (Fig. 5). Shifting channels at these intersections appear to have favored

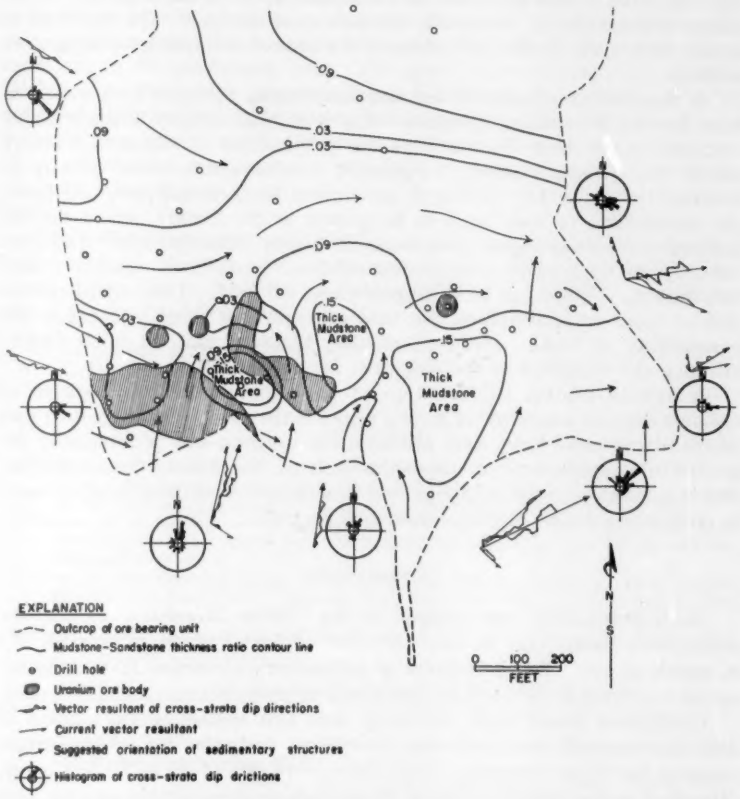

FIG. 5. Orientation of primary sedimentary structures, Three Point Mesa, Apache County, Arizona.

rapid burial and preservation of logs and plant debris. These factors may also have indirectly favored mineralization through creation of favorable permeability as well as by the accumulation of organic material which later became the precipitating agent.

Previous work on the Morrison formation in other areas suggests that the intersection of ancient currents may have favored later uranium mineralization. Mr. C. N. Holmes (2) noted that at Calamity Mesa, Colorado, the intersections of ancient stream meanders formed favorable environments for uranium mineralization and that mineralized areas were generally aligned with the ancient current directions. In the Thompson district, Utah, Stokes (8) describes a concentration of mineralization in broad meander curves where intersections of crescentric channels were common. On the basis of earlier field work, Stokes had advanced the idea of sedimentary uranium ore controls.

A decrease in velocity of the uranium-bearing solutions is assumed to have favored uranium precipitation. The interstitial velocity of mineralizing solutions would have decreased as the permeability of the rock through which they passed increased. (Quantity = cross-section times velocity in a closed system.) The sorting of the clastics tends to improve, and hence the permeability of rock tends to be greater at the locality, where the depositing currents changed from lower to higher velocities (3). Different velocities of the ancient currents are reflected by different types of cross-stratification. These can be distinguished in the field. Thus, by identification of types of stratification the field geologist can roughly compare the permeability of rocks. He must assume, however, that all other factors affecting the deposition of the sediments remained constant.

A definite relation between type of cross-stratification and location of uranium deposits was noted in several places in the area. This suggested that where two or more types were available, the uranium was preferentially deposited in a certain type of cross-stratification. Mineralized cross-stratification is not always of the same type, but mineralization has been most common in cross-strata deposited from faster local currents.

APPLICATION

Cross-stratification was mapped in the Chuska Mountains so that the sedimentary trends may be used for more efficient location of holes drilled in search of ore. The orientation of sedimentary structural features is assumed to control, by permeability, the trends of uranium mineral concentration.

Conclusions drawn from this study were first applied to the location of drill holes behind seven outcrops of uranium orebodies for which surface mapping had been completed. Drill holes were spaced 25 to 50 feet apart, depending on the expected width of the orebody as shown by the outcrop, and were located from 50 to 100 feet behind the outcrop. Cross-stratification directions along at least 300 feet of outcrop were averaged and this average was plotted through the center of the outcrop of the orebody. A line of three drill holes was then centered on this line (Fig. 3-A). Of the seven orebodies developed by the method described, six proved to be aligned within 20° of the average cross-stratification direction. This saved unnecessary drilling which might have been expended in "hit-or-miss" drilling behind the outcrop.

A second application of cross-stratification mapping is its use as a supplement to data of subsurface maps. The most successful subsurface exploration aid in the North Chuska Mountains area is the use of sandstone color from drill hole data. The first iso-color maps were made by the writer in 1951. The relation of alteration colors to uranium deposits had, however, been noted by earlier writers (10). Carnotite-type uranium orebodies in the North Chuska Mountains area are, in most places, surrounded by alternation or bleached zones in which the normal red color of the lower Morrison sandstone is tan or gray. The iso-color map is drawn on the percentage of altered sandstone in the ore-bearing unit. The areas of greatest thickness of gray sandstone on the contour map constitute a favorable zone in which orebodies are most likely to be found. Experience shows that these altered zones are generally elongated along the direction of the sedimentary structural feature. Cross-stratification mapping can, therefore, be used to project the altered, favorable zones from their outcrops along the direction of the ancient current flow.

The sedimentary structural features mapped are divergent in direction, both in any specific horizon and between horizons. This is a limiting factor in the application of the technique and projection is considered reliable for only a few hundred feet.

U. S. ATOMIC ENERGY COMMISSION,
GRAND JUNCTION, COLO.,
Nov. 23, 1954

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PROGRESS IN RADIOACTIVE IRON OXIDES INVESTIGATIONS [1]

TOM G. LOVERING

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ABSTRACT

The compilation of data on uranium and thorium deposits in various western states has shown that many of these deposits are closely associated with zones of secondary radioactive iron minerals. A study of these radioactive "limonites" was therefore undertaken in an attempt to find out in what form the radioactive material is present in the limonite, how it was introduced, and whether a field study of leached ferruginous cappings over uranium and thorium deposits might yield information about the depth, distribution, size, and grade of underlying ore bodies. This investigation consisted largely of a detailed study and analysis of many samples generously contributed by others—samples containing from 0.001 to 0.7 percent uranium, from 0.003 to 5.3 percent equivalent uranium, and from 0.001 to 4.16 percent ThO_2.

It is concluded that uranium minerals in an oxidizing sulfide environment go into solution in acid sulfate waters as uranyl sulfate in the presence of ferric sulfate. When these acid waters are neutralized, ferric sulfate hydrolyzes to form colloidal ferric oxide hydrate. This adsorbs the uranyl ion and thus removes most of the uranium from solution. As the colloidal ferric oxide hydrate ages, it crystallizes to form goethite and in this process most of the uranium is expelled to form particles of secondary uranium minerals in the resulting limonite. Most thorium minerals are resistant to weathering and remain in their original form in thorian limonites.

INTRODUCTION

In the western United States secondary radioactive iron oxides commonly occur in association with deposits of uranium and thorium. This association has been noted with a wide variety of radioactive source materials—with hydrothermal pitchblende-bearing veins in pre-Cambrian igneous rocks, with thorite deposits in metamorphic rocks, and with deposits of uranium vanadates and phosphates in sedimentary rocks. Some secondary iron oxides that are apparently unrelated to uranium or thorium deposits also show appreciable radioactivity. The presence of radioactive limonites near uranium and tho-

[1] Publication authorized by the Director, U. S. Geological Survey.

rium deposits has long been used as a field guide by geologists and prospectors in various districts, but few people realize how common the association really is. Radioactive limonite has been found over uranium and thorium ores but most occurrences of radioactive limonite have not been shown to be related to such deposits. This poses a major question: do these radioactive limonites have any characteristics that will enable a field geologist to determine whether they are genetically related to nearby deposits of uranium or thorium ore? The problem of establishing criteria for the interpretation of radioactive limonites entails several related questions: 1) how is the radioactive material held by the iron oxides; 2) what chemical processes are responsible for the combination; 3) can a study of the iron oxide capping over a uranium or thorium deposit yield any information about the depth, distribution, size and grade of ore bodies beneath?

"Limonite" is used in this report to mean any secondary iron minerals in the zone of oxidation; "limonite" commonly consists of mixtures of goethite and hematite with minor amounts of jarosite or siderite, and rarely of lepidocrocite. "Gossan" is used to mean the limonite-rich outcrop over an oxidizing sulfide ore body.

There is little published information available on the sampling and analysis of radioactive limonite. However, an unpublished report by Horne (11) states that a radioactive soil sample from a volcanic area in East Africa near the Kenya-Uganda boundary contains 0.004 percent U_3O_8 and 0.006 to 0.41 percent ThO_2; more than 90 percent of the radioactivity of this sample is associated with finely divided goethite and hematite. An experiment showed that these ferric oxides strongly adsorb and remove radioactive elements from solution (11).

METHODS OF INVESTIGATION AND RESULTS

After initial library work, a number of grab samples of radioactive and nonradioactive iron oxides were analyzed and the analytical data were compiled. These samples came from various places in the western United States and were submitted largely by geologists of the U. S. Geological Survey. The information obtained on each specimen varied with the nature and size of the sample, but in the more detailed studies it included: the location, geologic environment, hand specimen description, petrographic description of thin and polished sections, autoradiographs, analysis for radioactivity, semiquantitative spectrographic analyses for 36 elements, quantitative chemical analyses for FeO, Fe_2O_3, SiO_2, Cu, Pb, Zn, MnO, and S, differential thermal analysis, and X-ray (powder diffraction photograph) studies.

Sixty-two limonite samples from forty localities in eight states were received during 1952 and the first six months of 1953. Analyses of radioactivity are available on forty of these samples; twenty of them contain more than 0.01 percent uranium and ten contain more than 0.01 percent Th.

Megascopic studies on radioactive iron-oxide samples have thus far yielded relatively little information. No radioactive limonite sample exhibiting a relict boxwork or sponge texture has yet been received. Most of the samples contain ferruginous minerals either as a cement between quartz grains or as

a thin coating on fracture surfaces; the few exceptions consist of dense massive limonites that are so fine grained as to appear amorphous. The color of the limonite samples that contain more than 0.05 percent uranium ranges from a light-yellow ocher through various shades of yellow brown, orange, and chocolate brown to a very dark brown; the following color symbols on the National Research Council rock color chart distributed by the Geological Society of America are characteristic of these rocks: 10YR-7/4, 10YR-6/6, 5YR-5/6, 5YR-3/4, and 5YR-2/2. The red browns and reds are notably lacking. Most of the high thorium limonites, on the other hand, have a distinctly reddish color.

Only a few thin sections cut from radioactive limonite samples have yet been examined petrographically. Distinct uranium minerals are visible under the microscope in nearly all the samples that contain more than 0.05 percent uranium. One section showed a highly radioactive sooty black mineral that resembles pitchblende in appearance, intimately intergrown with goethite; in another, a veinlet partly filled with uranophane cuts massive goethite. Also, in the thorium-rich samples, intense radioactivity is usually traceable to small grains of thorite, but a few of these samples produced noticeable background fog on autoradiographs, suggesting that some thorium was present in the limonite, possibly as microscopic thorite particles.

A study of spectrographic and chemical analyses of twenty-five samples showed no element consistently associated with uranium.[2] Thirteen of these samples contained 0.01 percent or more of uranium; of this group nine were high in arsenic, seven were high in zinc, seven were high in cobalt, six were high in molybdenum, five were high in copper, and five were high in vanadium. (In this report a sample is defined to have a "high concentration" of an element if the element is present in amounts equal to or more than 10 times the average of all samples analyzed in the group.) Of the twelve samples that did not show significant concentration of uranium, six were high in arsenic, five were high in cobalt, three were high in molybdenum, three were high in zinc, three were high in vanadium, and two were high in copper. Data on arsenic are not available on three of the samples containing high uranium. Data on molybdenum assays are not available on three of the samples containing low uranium. This information is summarized in Table 1.

These data are admittedly insufficient to furnish a basis for reliable conclusions on the usefulness of any of these elements as a guide to uranium. From the available evidence it seems possible that in some districts the concentration of certain elements may show a close correlation with that of uranium, but in other districts such correlation may be lacking.

Thorium, unlike uranium, shows a fairly consistent suite of associated elements in the few high thorium limonite samples on which analyses are now available. These elements are chromium, niobium, and the rare-earth elements cerium, lanthanum, neodymium, and samarium. Only about half the samples high in thorium are high in these elements, but all the samples that are high in these elements are also high in thorium.

[2] Spectrographic analyses by P. J. Dunton; chemical analyses by Harold Levine, Jesse Meadows, and E. C. Mallory, Jr.

TABLE 1

PERCENT OF SAMPLES TESTED, CONTAINING AT LEAST 10 TIMES THE AVERAGE CONCENTRATION OF THE SPECIFIED ELEMENT *

High concentrations	A > 0.01%U**	B < 0.01%U**	Ratio A/B
Arsenic	90 (10 samples)	50 (12 samples)	1.8
Zinc	54 (13 samples)	25 (12 samples)	2.2
Cobalt	54 (13 samples)	42 (12 samples)	1.3
Molybdenum	67 (9 samples)	33 (9 samples)	2.0
Copper	38 (13 samples)	17 (12 samples)	2.2
Vanadium	38 (13 samples)	25 (12 samples)	1.5

* Concentrations determined by semiquantitative spectrographic analyses, P. J. Dunton, analyst.

** Figures inside parentheses are total number of samples analyzed.

Quantitative chemical analyses for FeO, Fe_2O_3, Al_2O_3, and SiO_2 were made on twenty-two limonite samples [3] and the results were plotted against concentrations of uranium and thorium. No consistent relationships were evident from the resulting graph (Fig. 1). It was noted, however, that all the samples with an FeO content greater than 3 percent contained pyrite.

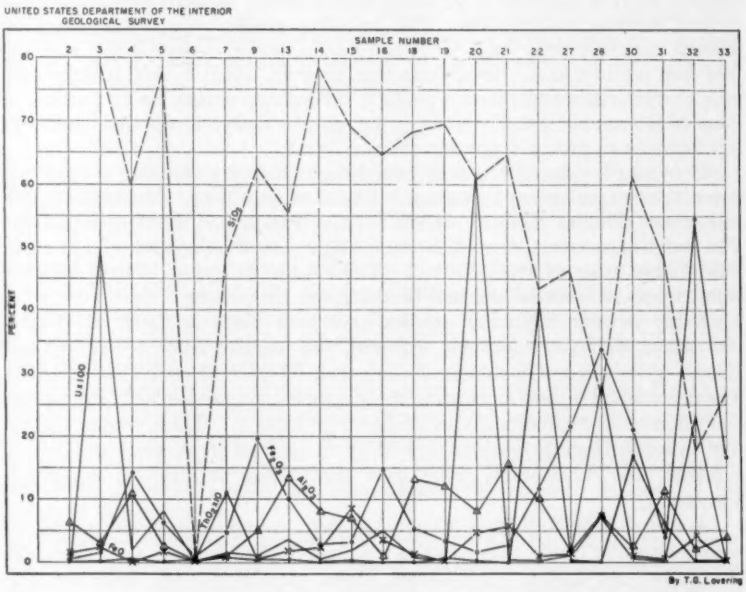

FIG. 1. Graph showing relative amounts of U, ThO_2, SiO_2, Al_2O_3, FeO, and Fe_2O_3 in limonite samples.

[3] Harold Levine, Jesse Meadows and E. C. Mallory, Jr., analysts.

The silica content of the samples ranges from 1.14 percent to 87.86 percent (in sample no. 2) and averages about 56 percent; the alumina content ranges from 0.22 to 15.47 percent and averages 6.7 percent; the ferric oxide content ranges from 0.55 to 54.66 percent and averages 11.7 percent; and the ferrous oxide content ranges from 0.00 to 8.18 percent and averages 2.24 percent.

Autoradiographs were made from polished sections of 10 samples containing large amounts of secondary iron and manganese oxides. Four samples were high in uranium, three were high in thorium, two were high in radium associated with barium sulfate, and one was low in all three elements with just enough uranium (0.01 percent) to expose the film slightly after 23½ days. All of the samples high in uranium or high in thorium produced small local black dots on the film, which were usually traceable to discrete mineral particles in the polished section. The background fog produced by the iron oxide cement was slight, especially in the samples containing uranium. The two specimens whose radioactivity was largely due to the presence of radium showed much more background fog, but these also produced local black spots and bands, indicating an uneven distribution of radioactive material although on megascopic examination, the specimens appeared homogeneous.

A number of powdered samples were tested on a portable differential thermal analysis machine in an effort to distinguish between goethite, lepidocrocite, siderite, and jarosite. The resulting graphs were checked against mineral determinations made by X-ray studies, and also against the quantitative iron oxide assays. It appears that goethite, siderite, and jarosite each give characteristic endothermic peaks if the mineral makes up 10 percent or more of the sample tested. None of the samples analyzed contained sufficient lepidocrocite to give a diagnostic thermal break.

One sample was run on a thermal balance, but the resulting weight loss curve showed no strong inflections. Chemical and X-ray data indicate that this sample contains about 13 percent Fe, nearly all of it in the form of jarosite. The weight loss curve showed two very slight, broad inflections, one at about 400° C, the other at about 700° C. These correlate approximately with the endothermic differential thermal breaks given by jarosite.

X-ray powder diffraction studies have been made on twenty-two samples whose equivalent uranium, uranium, and thorium contents are known.[4] Eleven of these samples contained more than 0.1 percent equivalent uranium. The distribution of iron minerals in these samples as revealed by X-ray studies and differential thermal analyses is shown in Table 2. These results suggest that uranium-bearing limonites are likely to be high in goethite and low in hematite, but considerably more data are needed to test this hypothesis adequately.

A sample from Fall River County, S. Dak., contained carnotite associated with specks and bands of goethite in a white bleached zone of a red hematitic sandstone. At Garo in Park County, Colo., cavities in a red sandstone contain crystals of tyuyamunite. Bands of red hematitic sandstone in white sandstone at the same deposit have outer rims of brown limonite (goethite?), and

[4] A. J. Gude, III and W. F. Outerbridge, analysts.

TABLE 2

DISTRIBUTION OF IRON MINERALS IN 11 LIMONITE SAMPLES WITH A RADIOACTIVITY GREATER THAN 0.1 PERCENT EQUIVALENT URANIUM *

Iron mineral	>0.05% U					>0.1% Th, <0.05% U				<0.1% Th, <0.05% U	
	1	2	3	4	5	6	7	8	9	10	11
Pyrite	X										
Siderite	X					X	X				
Hematite						X	X				
Goethite	X	X	X	X	X	X		X	X		X
Lepidocrocite	X	X									
Jarosite										X	
Unidentified manganese oxide											X

* Analyses determined by X-ray powder diffraction photographs and differential thermal analyses in the laboratories of the U. S. Geological Survey; A. J. Gude III, W. F. Outerbridge, P. D. Blackman, and C. J. Parker, analysts.

these in turn are bordered by a yellow zone containing disseminated tyuyamunite. On the other hand, a sample of silicified red hematitic sandstone from the vicinity of Joseph City, in Navajo County, Ariz., contains 0.08 percent uranium but no uranium minerals are visible in the specimen. It thus appears that there are notable exceptions to the generalization that uranium does not occur associated with red hematite.

DISCUSSION

A primary ore body consisting largely of pyrite, with subordinate amounts of pitchblende in a relatively nonreactive gangue, should be chemically unstable in the zone of oxidation. According to Bateman and Emmons (2), (5), (6), the pyrite oxidizes and dissolves with the formation of ferrous sulfate and sulfuric acid; ferrous sulfate in turn oxidizes to ferric sulfate and ferric hydroxide;[5] and finally the ferric sulfate breaks down to yield ferric hydroxide[5] and more sulfuric acid. Foreman (8) states that the presence of H_2S in solution will inhibit the solution of the sulfides and precipitate sulfides from acid sulfate solutions.

Decomposing organic matter in sedimentary rocks might furnish hydrogen sulfide, and even after decomposition, carbonaceous material in the presence of calcium carbonate can reduce iron sulfate solutions, with the precipitation of iron sulfide, according to Thiel (21). This mechanism might explain the association of sulfides with carbonaceous material in some deposits of the Colorado Plateau.

On the other hand in an oxidizing environment near the surface, where H_2S and carbonaceous matter are absent, pyrite should break down to the ferrous sulfate and sulfuric acid. McBaine (15) states that the oxidation of ferrous sulfate to ferric sulfate is not noticeably affected by H_2SO_4 in concentrations less than 0.5N.; the reaction is facilitated by high concentration of

[5] Ferric hydroxide hydrolyzes rapidly to form ferric oxide hydrate.

oxygen and $FeSO_4$, and by high temperature. This oxidation would be further facilitated by gamma-radiation from any uranium associated with the sulfide as shown by Amphlett (1) and Hardwick (10). Ferric oxide hydrate forms by the hydrolysis of ferric sulfate on neutralization of the acid solution or by simple dilution at a pH of about 3. It is precipitated as a gelatinous hydrosol, which after aging and partial dehydration yields goethite ($Fe_2O_3 \cdot H_2O$). The rarer dimorphous form of ($Fe_2O_3 \cdot H_2O$), lepidocrocite, is formed by the oxidation of hydrous ferrous iron compounds according to Rooksby (20). The work of Guild (9) and Peacock (16) indicates that goethite yields hematite by dehydration, lepidocrocite yields magnetic ferric oxide or maghemite. Tunell and Posnjak (22) have demonstrated that in the Fe_2O_3—H_2O—SO_3 system goethite is the stable form below 130° C, hematite above that temperature. This may help to explain why, in supergene deposits, uranium is commonly associated with goethite rather than hematite.

Secondary limonite minerals may be derived from ferruginous carbonates as well as from pyrite. In this paper emphasis has been placed on limonite of sulfide derivation because of the close association between pyrite and uranium oxides both in the vein deposits of the Colorado Front Range and in the sandstone deposits of the Colorado Plateau. Siderite is present, however, in many thorian limonites, and recent studies of carnotite deposits in South Dakota indicate that uranium may have been precipitated with iron-manganese carbonates. Limonite formed from these carbonate deposits should be radioactive (L. R. Page, oral communication).

Pitchblende is also unstable in an oxidizing acid environment. This mineral is commonly assigned the formula UO_2; actually it does not have a fixed composition but consists of a mixture of UO_2, UO_3, and daughter products such as Ra and Pb in varying proportions. The UO_3 present in pitchblende easily breaks down to form UO_3 hydrates, which are fairly stable under ordinary atmospheric conditions but readily soluble in acid sulfate waters. UO_2, on the other hand, does not readily form a hydrate, nor is it susceptible to attack by dilute H_2SO_4 according to Katz and Rabinowitch (12). This results in differential leaching of UO_3 and residual enrichment of UO_2, Pb, and Ra, where pitchblende is subject to attack by sulfuric acid solutions, as has been shown experimentally by Phair and Levine (17). Recent investigation by Kraus and Nelson (13) indicates that the UO_3 hydrates go into solution to yield the uranyl ion $[UO_2]^{++}$, and in acid sulfate solutions this may form complexes such as $(UO_2)(SO_4)_2^{=}$ or $(UO_2)(SO_4)_3^{\equiv}$. Uranium is precipitated from acid solutions when they are neutralized; the pH at which this takes place is a function of the original concentration of $[UO_2]$. A decrease in $[UO_2]$ concentration from 1 percent to 0.1 percent raises the precipitation pH from 4.5 to 6.0. At high dilution uranium can remain in solution as the solution goes from acid to alkaline. In alkaline solutions it is present as the uranate (UO_4) or diuranate (U_2O_7).

Because the ionic radius of U is about 1.05 as given in Katz and Rabinowitch (12), and that of Fe is about 0.67 it is unlikely that U would substitute for Fe in minerals formed from a uranium-bearing ferric hydroxide hydrosol.

The uranyl ion [UO_2] is strongly adsorbed on hydrosols of Fe, Si, or Al according to Rankama and Sahama (18), and Rodden (19) states that ferric oxide hydrate will remove U from solution down to a concentration of one or two parts per million.

Thus it appears that uranium originally present as pitchblende would be adsorbed by colloidal ferric oxide hydrate and subsequently, when the ferric oxide hydrate crystallizes, the uranium is expelled to form any of a variety of secondary uranium minerals, depending on the environment. In the absence of some such adsorbing or precipitating agent dilute uranium-bearing solutions could move for long distances since a change from acid to neutral or alkaline conditions alone might not cause precipitation.

Thorium minerals are more stable than uranium minerals in the zone of oxidation and tend to form mechanical concentrations according to Fersman (7). However, Rodden (19) says that ThO_2 (thorianite) that has not previously been heated above 600° C is slightly soluble in dilute H_2SO_4. $[Th]^{+4}$ is removed from solution by $Fe_2O_3 \cdot nH_2O$. It co-precipitates as thorium hydroxide, which slowly goes over to the more stable thorium oxide hydrate.

The end product of the alteration and leaching of sulfide ore bodies, the limonitic gossan, has been carefully studied by Emmons (5) (6), Locke (14), Blanchard and Boswell (3) (4), Bateman (2) and others.

The mineral assemblage and texture determines the nature of the leached outcrop. In finely disseminated sulfide deposits, the sulfide particles are commonly too small to produce a relict sponge or boxwork; the outcrop of a coarsely disseminated or a massive sulfide deposit, on the other hand, commonly develops these textures. No sponge or boxwork textures were developed in any of the radioactive limonite samples examined by the author; hence the original mineral assemblage is not known, but presumably it did not consist of massive sulfides. The chemical processes involved in the leaching of a pyrite-bearing outcrop have been previously discussed.

Boswell and Blanchard (4) have determined that "limonite" gossans consist largely of goethite, hematite, silica, sulfates of iron and lead, and rarely lepidocrocite. The color of a limonite may be diagnostic of the primary minerals producing it, according to Bateman (2); this color depends on the composition, the degree of hydration, and the size of the grains. The color of transported limonites is a less reliable criterion of the primary minerals from which they were derived than that of indigenous limonites.

Only a few samples containing indigenous limonite associated with pyrite and pitchblende have thus far been collected by the author. In all of these the color is dark brown (5 YR 2/2–5 YR 3/4). The color of transported radioactive limonite varies widely.

SUMMARY

The results of this study suggest a few hypotheses about the effects of oxidation on an ore body consisting of a mixture of iron and uranium minerals as contrasted with one consisting of iron and thorium minerals.

Uranium minerals dissolve in the acid sulfate waters produced in an oxidizing sulfide body. Uranium probably is carried in these waters either as

uranyl ion or as uranyl sulfate complex. As these acid waters become neutralized, either by reaction with wall rocks or by dilution, iron, which is present as ferric ion, hydrolyzes to form colloidal ferric oxide hydrate. This $Fe_2O_3 \cdot nH_2O$ sol, together with any colloidal silica present, coagulates and precipitates; the uranyl ions probably are adsorbed on the surface of the colloidal particles and removed from solution. As ferric oxide hydrate ages and dries, it crystallizes to form the mineral goethite. Because uranium has a much larger atomic diameter than iron, it presumably cannot substitute for iron in the space lattice of goethite. It is, therefore, excluded from the crystal structure and forms distinct secondary uranium minerals scattered through the "limonite."

In the author's experience uranium or uranium minerals are rarely associated with secondary hematite, but a few radioactive hematite gossans are known. The ratio of hematite gossans to goethite gossans is very small, and the scarcity of radioactive hematite may largely reflect this relation.

Thorium is most frequently found in such minerals as thorite and monazite, which do not readily decompose in the zone of oxidation. Most of the high thorium limonite samples that have been studied contain grains of thorite or hydrothorite in a matrix of iron oxide and quartz. This is to be expected because thorium, like uranium, has a much larger atomic radius than iron. Thorium, however, differs from uranium in that it does not readily form a soluble thoranyl ion in weakly acid solutions. On the basis of this preliminary study, it appears probable that, unless the ore has a primary zoning, the tenor of thorium in oxidized outcrops should closely approximate the grade of primary ore at depth, allowing for the porosity of the gossan. No such generalization for uranium deposits can be made.

ACKNOWLEDGMENTS

The data presented in this paper are almost entirely based on a review of the available literature and on analytical results furnished by X-ray, spectrographic, and chemical analyses of selected samples. The author is indebted to colleagues in laboratories of the U. S. Geological Survey for their invaluable technical services and to the many geologists who collected samples for him. This work was done on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission.

U. S. GEOLOGICAL SURVEY,
DENVER, COLORADO,
Dec.. 27, 1954

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MINERALOGY OF A URANINITE-BEARING PEGMATITE, LAC LA RONGE, SASKATCHEWAN

ROBERT B. FORD

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ABSTRACT

The Nunn Lake uraninite pegmatite is a large, well-zoned sill-like body. Uraninite occurs within the outer three feet of the wall zone, as sheet-like masses within an aplitic phase of the pegmatite, and as late fracture fillings.

Deposition of the uraninite took place in two stages. The first stage was crystallization within and contemporaneous with the potassium-rich wall zone. The second stage was the crystallization of the uraninite within aplitic phases of the pegmatite and as late fracture fillings. This second stage of uraninite crystallization is in direct association with a mineral assemblage that is evidence of a late residua of alkali potassium silicate and the acid radicals of the halides.

INTRODUCTION

THE Nunn Lake area is located in north central Province of Saskatchewan along the margin of the Precambrian shield, at longitude 104° 20′ and latitude 55° 15′. The vicinity is readily accessible by air or canoe route from Lac La Ronge, some fifty miles to the southwest (Fig. 1).

The pegmatite was originally examined by R. J. Claus and R. B. Ford and claims were filed by them in September 1949. This paper is a result of investigations by the above in the following year. In studying the uraninite occurrence, trenching and blasting were done to identify peripheral zones and fractures, which alone contain uraninite (cleavite) crystals of unusually large size. These cubic crystals are as much as 1.25 inches in cross section.

This paper is essentially descriptive and covers zonal arrangement and mineralogy of the pegmatite. Such correlative aids proved invaluable in both prospecting and exploration. The lithologic and structural units recognized

by detailed studies in the United States (1)[1] are employed herein for obvious reasons of simplicity and conformity.

The writer is indebted to Richard J. Claus for his help in preparing the maps, and the University of Wisconsin for use of the laboratory facilities.

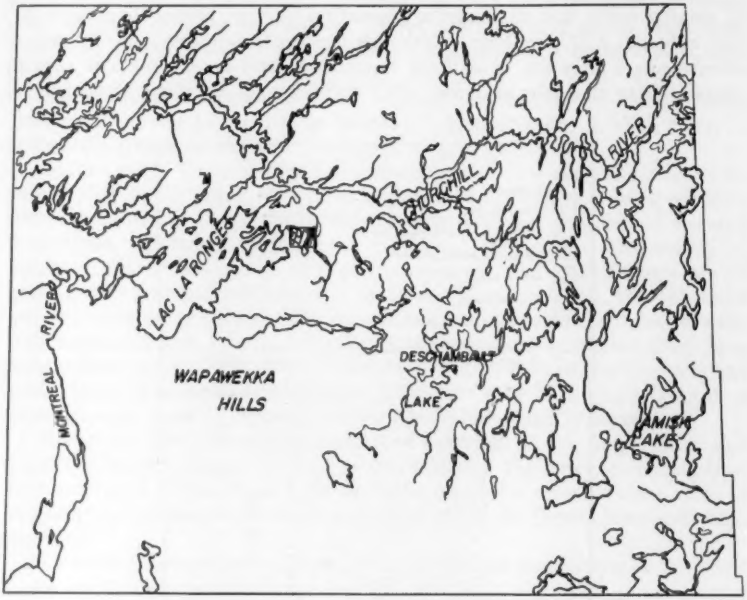

FIG. 1. Map showing the location of Nunn Lake area Churchill Mining District.

GENERAL GEOLOGY

The consolidated rocks of the area are considered by M. L. Keith (3) to be of the Wekusko group of Archean Age. These altered meta-sediments around Hunter Bay and Nunn Lake contain sub-angular to round fragments of quartz and feldspar subjected to a neo-mineralized matrix of quartz, feldspar and mica. These graywackes are commonly interbedded with quartz-

[1] Numbers in parentheses refer to Bibliography at end of paper.

hornblende gneisses, giving a banded appearance. The sediments are extensively invaded by acidic intrusives. Contacts and surfaces are extremely well exposed, with a dearth of vegetation, an attestation of pegmatitic bodies. Glacial striae and plucking are evident and give a well cleaned surface.

The pegmatites vary in size and composition. Bodies less than 3 feet long of varying strike and dip range to pegmatites of huge proportions, some 800 feet wide and 2,500 feet long. Although the pegmatites traverse sediments of diverse origin they are of uniform composition and have a metallic content characteristic of acidic granites. The derivation of the pegmatites from a

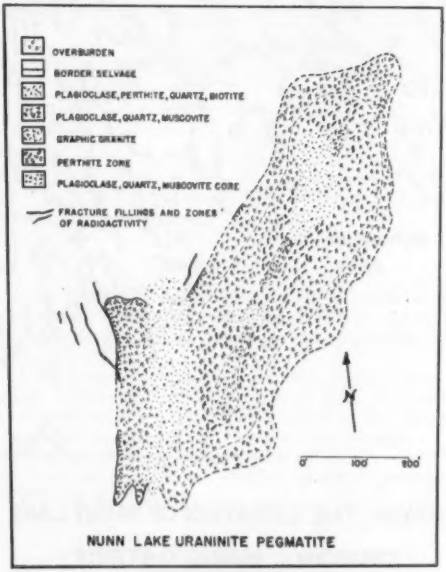

FIG. 2. Nunn Lake uraninite pegmatite.

resolute granitic source can scarcely be argued. The distribution and orientation of the pegmatites have seemingly been governed by structure of the country rock. The shape of the pegmatites is chiefly lenticular, reflecting the strongly foliated character of the containing rocks.

The Nunn Lake uraninite pegmatite, 700 feet long and 300 feet wide, is concordant with the strike of the regional foliation at N 20° E, and seemingly dips parallel to the lineation of the gneissic country rock at 70° WNW. This concordance is continued in the zonal arrangement. The entire central portion is exposed with the north and east boundaries limited in outcrop and bordered by heavy drift and bogs (Fig. 2).

INTERNAL STRUCTURE

General Statement.—Concentration of economically important pegmatite minerals occurs in zones, distinct from adjacent barren units. That is to say, homogeneous pegmatites rarely if ever contain any desirable mineral content. The distribution of minerals and texture irregularity serve to identify separate units in heterogeneous pegmatites. These units, termed zones, have been defined by Jahns (2) as successive shells concentric about an innermost zone or core.

Classification of zones follows the method proposed by the United States Geological Survey (1) and is as follows: 1. Border zone; 2. Wall zone; 3. Intermediate zone or zones; 4. Innermost zone or core.

Border zones are generally fine grained and seldom over a foot in thickness. Most border zones have never enjoyed the distinction of being separate from the adjoining wall zones because of their relatively insignificant size and importance. Detailed studies have confirmed the general consistency of border shells or selvages to any given pegmatite (1). Wall zones are of greater thickness and coarseness of texture. Mineralogically, the difference between these outer zones is not great. Intermediate zones occur between the wall zones and core. Seldom is a pegmatite described with more than three intermediate zones. The core may be absent but consists of coarse quartz and acidic plagioclase when it is present. The core may be a single body or a discontinuous chain of regular or irregular bodies centrally located.

Structural units other than zones are generally of less importance, and consist of fracture fillings and replacement bodies. The latter are mostly fracture controlled. The Nunn Lake uraninite pegmatite owes its chief mode of uraninite occurrence to late fracture fillings within the border zone and country rock.

Detailed Observations.—The sequence of mineral assemblages in the Nunn Lake uraninite pegmatite based on field investigation of the more essential minerals from the wall rock inward is as follows: (1) biotite, orthoclase; (2) plagioclase, perthite, quartz, biotite; (3) plagioclase, quartz, muscovite; (4) graphic granite; (5) perthite, quartz and (6) plagioclase (albite), quartz, muscovite (Fig. 2).

Border Zone.—The country rock bordering the pegmatite is of granular texture consisting largely of hornblende ($2V = 84°$, $Z \wedge C$ 24°), quartz, and albite (An 7). Biotite, other than along foliation planes, is uncommon. Magnetite and apatite are sparsely distributed, with sillimanite forming at the expense of biotite. The quartz and plagioclase are unsutured, granular fragments, with the hornblende more idioblastic. Away from the contact the hornblende loses its green color and the amount of feldspar decreases. The country rock has been subjected to impregnation and assimilation by the pegmatite, producing a broad continuous belt of micaceous biotite selvage (Fig. 3). This selvage, or border zone, is less conspicuously a part of the pegmatite although the contact of this zone is sharply unconformable with the country rock. The biotitization has produced massive micaceous flakes oriented subperpendicularly to the wall zone. The omnipresent selvage is from 2 to 7

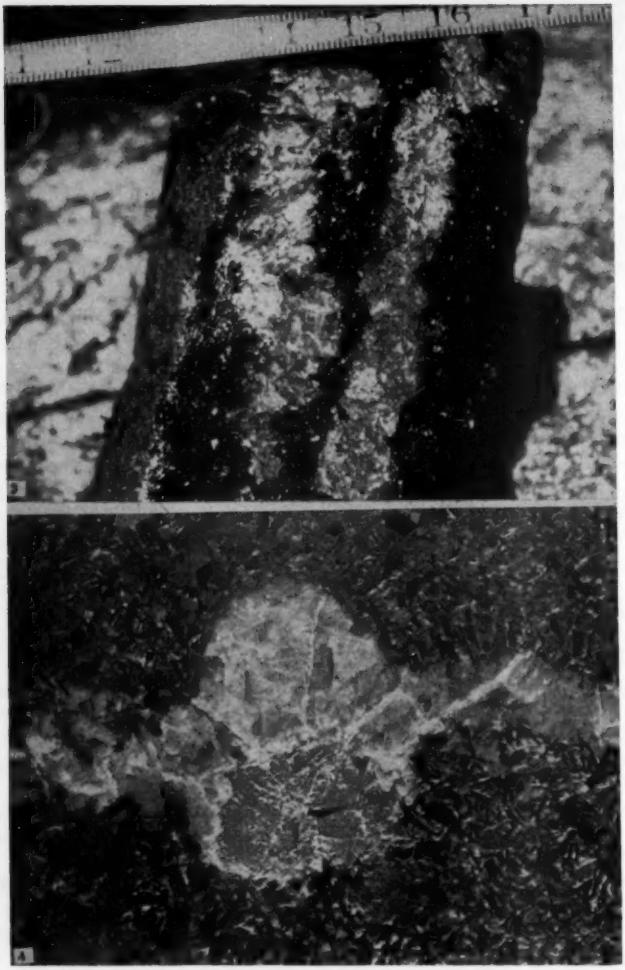

FIG. 3. Apophyses of orthoclase feldspar within border selvage. Emplacement accompanied by movement.

FIG. 4. Uraninite in characteristic "Atoll" development, associated with stringers of lake potash feldspar and quartz. × 1.5.

inches thick. Apophyses of orthoclase feldspar from $\frac{1}{16}$ to 2 inches wide parallel the border of the pegmatite where they invade the selvage. Along these aphophyses the biotite flakes show rotation with evidence of shear. Emplacement was accompanied by movement (Fig. 3).

The massive biotite selvage contains metacrysts of plagioclase (An 7) with inclusions of smaller biotite flakes, hornblende ($2V = 84°$, $Z \wedge C$ 24°), zircon, apatite, and magnetite. Monazite, a phosphate of cerium and thorium, and fluor-apatite are common constituents of this border selvage and appear as euhedral crystals later than and replacing plagioclase and biotite.

The monazite is colorless to yellowish in thin section with prominent cleavage parallel to (001). A brick-red decomposition product is evident. The feldspar surrounding this monazite is generally stained yellow brown in a reaction rim. In larger scale the discoloration extends several inches around concentrations of sufficient mass. The cubic uraninite shares micro-cross fractures with the monazite. These fractures are filled with a yellow-brown micaceous and fibrous mineral of isotropic character. Reaction rims about both monazite and uraninite are also characterized by such material, which is thought to be limonite. A second form of uraninite, located in the border selvage, probably reflects more clearly the intimate association of uranium with the late residuum of alkali silicate. Small "atoll" borders of orthoclase enclose an irregular crystal of uraninite. These "atolls" rarely exceed 1.5 centimeters in cross section. The association of these "atolls" with stringers of late orthoclase and quartz is a common feature (Fig. 4). The fractures and rims about these uraninite bodies are stained by the limonitic discoloration mentioned above.

Allanite, lacking cleavage but with typical subconchoidal fracture and brownish yellow color, is found invading biotite as a replacement phenomenon. These resinous bodies are characterized by a pleochroic halo effect on adjacent biotite.

Sericite is localized in plagioclase lamellae and orthoclase intergrowths, but has not affected the late orthoclase in immediate contact with the rare earth minerals.

Wall Zone.—The border selvage of the Nunn Lake uraninite pegmatite is followed by the wall zone. This wall zone is more coarsely grained and has a general thickness of five feet. The contact is sharp along the border selvage and is gradational inward. This zone contains the major amount of uraninite. The uraninite (cleavite) crystals associated with the quartz, perthite, plagioclase, biotite wall zone are of cubic habit and form (1) a sheet-like mass immediately inside the biotite selvage, and (2) isolated crystals largely within the outer three feet of the wall zone (Fig. 5). The outer sheet-like mass is peripheral to an aplitic phase of the wall zone. The idioblastic texture of the uraninite is more clearly seen farther from the contact. Velvet black color, greasy luster, and conchoidal fracture with extreme brittleness are easily recognizable features. Both zones of radioactivity are emphasized by minor amounts of orthoclase feldspar. The orthoclase adjacent to the uraninite has a fresh, unsericitized appearance although discolored by a red stain. The association of iron stain to uranium minerals is as characteristic in pegmatite

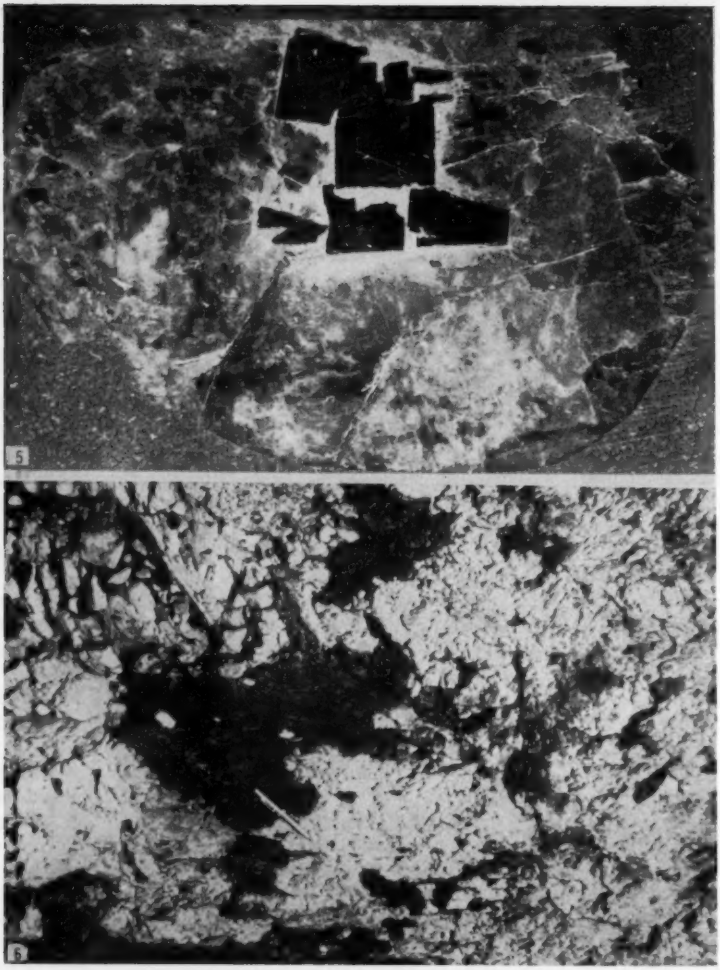

FIG. 5. Uraninite (cleavite) crystals embedded in late orthoclase, within the plagioclase, perthite, quartz, biotite wall zone. Note characteristic "bleaching." × 3.3.

FIG. 6. Muscovite books arranged in pod-like bodies within central zone or core.

bodies as it is in mineralized zones of less acidic rocks. The red coloration is thought by Thurlow and Wright to be due to disseminated hematite (6).

The main pegmatite minerals of this wall zone are perthite, plagioclase and quartz. Biotite plates four inches in cross section decrease in size and concentration inward. Zircon commonly produces pleochroic haloes within the biotite. The microcline contains patches and veins of sodic plagioclase in characteristic intergrowth form of perthite. The remaining plagioclase (An 30) is sericitized. Strain shadows and warped lamellae are common. The orthoclase feldspar is in minority with sutured boundaries and a fresh unsericitized appearance. This orthoclase is characterized by red staining and higher radioactivity. Aplitic texture commonly parallels the border in this zone with the textural difference immediately recognizable. Microscopically there is little difference in the chemical constituents of the aplitic and massive phases except for the advent of garnet within the aplitic phase.

Quartz is interstitial or in large pod-like forms within this zone. It commonly shows color variation between a very black or smoky quartz to a yellowish and white variety, the smoky quartz being indicative of the presence of uranium minerals.

Intermediate Zones.—The intermediate zone is divisible into three genetically different zones. They are more irregular in continuation and maintenance of definite characteristics than either the wall zone or core. The outer plagioclase, quartz, muscovite zone is continuous. The intermediate graphic granite and innermost perthite, quartz zone merge along the strike. The texture of the intermediate zones is more coarse than the wall zone with an increase in coarseness toward the core. Giant crystals are most noticeable in the perthite, quartz zone.

The plagioclase, quartz, muscovite zone borders the wall zone and can be distinguished by color alone. The feldspar is much lighter in color, with the biotite sheets giving way to small flakes of muscovite. The plagioclase (An 24) is intergrown with quartz and has produced myrmekitic texture. The muscovite has crystallized in cleavage planes and minute fractures. Quartz has lost its color, but pods and interstitial quartz make up a greater percentage than is present in the wall zone.

In outcrop the plagioclase, quartz, muscovite zone is 20 to 30 feet wide and is continuous in linear arrangement. Asymmetrical development is characterized by the larger outcrop pattern on the northern end.

The graphic granite is coarse with large, regular, spindle-like quartz rods occurring in deep red perthite crystals. Pod-like masses of white quartz are irregularly distributed through this zone. The outcrop of this zone is parallel with the pegmatite wall and has a breadth of some 30 to 40 feet. This zone of graphic granite merges along the strike with the perthite quartz zone into a singular unit. The formation of microcline immediately around the quartz intergrowths is of common occurrence.

The pegmatite contains an incomplete perthite quartz zone that thickens in midsection and merges laterally with the graphic granite zone described above. The perthite consists of a microcline matrix with thin, platy and spindle shaped parallel lenses of sodic plagioclase in intergrowths. The thickness of many

perthitic intergrowths can be measured on outcrop and are one-fourth centimeter in maximum cross section.

Central Zone or Core.—Plagioclase, quartz, muscovite core features are well established in the southeastern section of exposed surface. The main segment of the core is 500 feet long and as much as 30 feet thick and is parallel to the general trend of the surrounding zones.

Mica books arranged in pod-like bodies (Fig. 6) as much as four and five feet across are not rare. The albite (An 7) matrix with interstitial quartz masses is the dominant characteristic. Graphic texture is evident with an absence of quartz masses within the boundaries of this textural feature.

Petrographically the core is coarse grained with albite showing slight sericitization. Small plates of muscovite are arranged within the albite boundaries.

Fracture Fillings.—The hornblende gneiss bordering the north side of the pegmatite contains several small fractures of intense radioactivity. Typical of these fractures was one followed by Geiger readings from the contact and striking north for 100 feet. It was exposed in a shallow trench about 25 or 30 feet west of the pegmatite contact. This zone of radioactivity was characterized by a complex mineralogy of orthoclase, biotite, magnetite, uraninite, monazite, allanite and fluor-apatite. The petrographic relationships were somewhat masked by limonitic staining.

The fracture filling described above was well exposed at the pegmatite contact where it merges with the aplitic phase of the wall zone. The fracture is plainly contemporaneous with the aplitic phase as it cuts the border zone but does not transect the wall zone.

Other fracture fillings are within the pegmatite. Several fractures transect the boundaries of the intermediate zones. These fractures are characterized by salmon-pink orthoclase feldspars and high radioactivity, although no radioactive minerals were found.

SUMMARY AND CONCLUSIONS

The Nunn Lake uraninite pegmatite shows evidence of two stages of uraninite crystallization. The association of both stages with the potassium-rich rocks is evident. The first stage is crystallization of the uraninite contemporaneous with the massive perthitic wall zone. It has been shown, however, that some of this uraninite within the wall zone is in direct association with a fresh, unsericitized aplitic and massive phase of orthoclase, and is considered to be part of the late second stage. The second stage of uraninite crystallization is described as being part of the late fracture fillings and aplitic phases of the pegmatite. The association of the potash feldspars with the uraninite is clearly shown in Figures 4 and 5, and is in accord with facts already known (4).

It is well known that at higher temperatures orthoclase may hold in crystal solution other feldspar molecules, chiefly albite, which at elevated temperatures seem to possess the same monoclinic lattice as orthoclase. On cooling, however, unstable conditions result and the dissolved molecules may separate.

Partial separation is evidenced by the perthitic structures; complete separation by the albite and orthoclase masses. It is because of the structural control and sequence of crystallization that these orthoclase masses have been considered to be the major portion of the end stage residuum. The late fracture fillings and aplitic phases of the Nunn Lake uraninite pegmatite are evidence of what this end stage residuum held in solution. There was a strong potassium residue associated with the acid radicals of the halides. The latter was probably in some combination with the rare earth elements. The common sericitization suggests that the combination was alkaline in its effects on the first crystallized rocks.

From experimental analyses of pegmatites by Smith (5) it is considered that the miscibility of rest magma and water phases is proportional to the sodium and potassium residue, and that these same alkalies combine with the acid radicals of the halides with a resultant increase in mobility. The Nunn Lake uraninite pegmatite suggests that a similar residue has been "filter-pressed" by dilatant action into aplitic phases within the outer wall zone and into late fractures mainly within the country rock, and that the second-stage uraninite has crystallized from this residue.

CRYSTAL FALLS, MICHIGAN,
July 9, 1954

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GEOCHEMISTRY AND MINERALOGY OF A URANIFEROUS LIGNITE[1,2]

IRVING A. BREGER, MAURICE DEUL, AND SAMUEL RUBINSTEIN

ABSTRACT

Detailed studies have been carried out on a uraniferous lignite from the Mendenhall strip mine, Harding County, S. Dak. By means of heavy-liquid separations, a mineral-free concentrate of the lignite was obtained that contained 13.8 percent ash and 0.31 percent uranium in the ash. The minerals (gypsum 69 percent, jarosite 10 percent, quartz 2 percent, kaolinite and clay minerals 19 percent, and calcite trace) contain only 7 percent of the uranium in the original coal, indicating an association of the uranium with the organic components of the lignite.

Batch extractions show that 88.5 percent of the uranium can be extracted from the lignite by two consecutive treatments with boiling 1 *N* hydrochloric acid. Continuous extraction with hot 6 *N* hydrochloric acid removes 98.6 percent of the uranium.

Columns of coal were treated with water, 1 *N* hydrochloric acid, 6 *N* hydrochloric acid, and a solution of lanthanum nitrate. The experiment with lanthanum nitrate indicated that only 1.2 percent of the uranium in the coal is held by ion exchange. The elutriation experiments showed that the uranium is held in the coal as an organo-uranium compound or complex that is soluble at a pH of less than 2.18.

A geochemical mechanism by which the uranium may have been introduced into and retained by the lignite is discussed.

INTRODUCTION

NUMEROUS field studies have been carried out on uranium-bearing carbonaceous deposits in the Dakotas, Montana, and Wyoming by the U. S. Geological Survey on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission. As early as 1946 A. L. Slaughter and J. M. Nelson reported uranium-bearing coal in the Red Desert region of southern Wyoming. As a result of their work other areas were examined in 1948 and 1949, and uraniferous coal was found in southwestern North Dakota by D. G. Wyant and E. P. Beroni, and in northwestern South Dakota by Beroni and H. L. Bauer, Jr. Further investigations in 1951 in these areas as well as in other western states resulted in the discovery of additional uraniferous coals by N. M. Denson and his coworkers.

In 1950 a program was established in the Geological Survey to investigate the origin, distribution, and occurrence of uraniferous lignites. A number of phases in this program are economic: minability of the lignite, utilization of

[1] Publication authorized by the Director, U. S. Geological Survey.

[2] This paper is taken in part from an administrative report prepared for the U. S. Atomic Energy Commission dated December 1952 and declassified June 1954. Part of this paper was presented before the Division of Gas and Fuel Chemistry of the American Chemical Society at its 126th meeting, New York City, September 1954.

the energy from combustion of the lignite, chemical use of the lignite compatible with the recovery of uranium from it, extraction of uranium from the ash of the lignite, and the possible extraction of trace elements from the lignite. The purposes of the geochemical and mineralogic phases of the program were: to study the distribution of uranium in the minerals and in the organic material to determine the conditions under which the uranium could be extracted from the organic material and the manner in which the uranium is held in the organic material and to establish the conditions under which the uranium could have been introduced into and retained by the coal.

Work on the coal from Harding County, S. Dak., was undertaken because this was the first area containing uraniferous lignites to receive a detailed field examination. The Mendenhall strip mine was chosen for sampling because it is the only locality in this area where a thick sequence of lignite is exposed.

Acknowledgments.—Cooperation and assistance of the following members of the staff of the Geological Survey are acknowledged: Mrs. Shirley Lundine for most of the uranium analyses, F. S. Grimaldi and Irving May for many helpful suggestions on the chemical problems, Charles Annell for the spectrographic analyses, and Edward Dwornik for the electron micrographs of the lignite separates.

COLLECTION OF SAMPLES

Investigations have been carried out in large part on a suite of samples collected in July 1952 from the Mendenhall strip mine, which is located about 6 miles south of Reva Gap in the Slim Buttes area in the NW1/4NW1/4SE1/4 sec. 1, T 17 N, R 7 E, Harding County, S. Dak. The coal occurs in the Ludlow member of the Fort Union formation of Paleocene age. The samples were collected by a group composed of Professors Spackman and Bates, Pennsylvania State University, research contractors for the Atomic Energy Commission, and N. M. Denson, H. D. Zeller, and R. Erickson, of the U. S. Geological Survey. At the suggestion of J. M. Schopf, of the U. S. Geological Survey, a columnar sample of the upper part of the Mendenhall coal was collected. This sample was submitted to Schopf for standard description and preparation prior to distribution for analysis. In the course of exposing the columnar sample, equivalent samples were collected and stored in 10-gal carbide cans. Details of the sampling procedure are given by Bates and Spackman (4). Denson and his coworkers, as a result of their extensive field investigations, had proposed that uranium was introduced into the coal by ground-water action subsequent to coalification.

MINERALOGIC STUDIES

The purposes of the mineralogic studies were to determine how much of the uranium present in lignites is combined with minerals and to identify whatever uranium minerals may be present, and to determine whether any of the minerals, regardless of their radioactivity, may be indicative of the presence of uranium in lignite.

To fulfill these purposes it was necessary to separate the minerals from the lignite, to identify the minerals, and to determine their radioactivity and uranium content. The separable minerals are only part of the total inorganic content of coal inasmuch as there is always some inorganic material in combination with the plant material and some very fine grained mineral matter that may be incorporated in the coal and may be essentially inseparable. When coal is ashed, the total inorganic material is represented by the ash. It was necessary, therefore, to compare the analyses of mineral-free coal ash, ashed mineral separates, and the original coal ash so that the most significant trace-element and minor-element relationships could be evaluated.

Separation of Minerals.—Several methods of mineral separation were tested and only float-sink separation in heavy-liquid media was found satisfactory for the relatively large-scale operations that were necessary. Almost all of the detailed mineralogic separations were carried out on two similar samples, both from the Mendenhall strip mine, Harding County, S. Dak.

TABLE 1

ANALYSIS OF LIGNITE FROM THE UPPER BED OF THE MENDENHALL STRIP MINE, HARDING COUNTY, S. DAK.[1]

	As received	Moisture free	Moisture and ash free
Proximate analysis			
Moisture, percent	44.8		
Volatile matter, percent	26.1	47.3	68.3
Fixed carbon, percent	12.1	22.0	31.7
Ash, percent	17.0	30.7	
Ultimate analysis			
Sulfur, percent	2.6	4.7	6.8
British thermal units	3080	5590	8070
Forms of sulfur			
Sulfate, percent	2.11	3.84	5.49
Pyritic sulfur, percent	0.09	0.16	0.23
Organic sulfur, percent	0.28	0.50	0.72

[1] Analyses by U. S. Bureau of Mines, Lab. No. D-90763, Oct. 2, 1952.

The first sample used in these studies was representative of the entire top bed columnar sample and was a split of the minus 1/4-inch material prepared by Schopf and associates for proximate, ultimate, and other standard analyses by the U. S. Bureau of Mines Coal Analysis Section (Table 1). The lignite was lightly rolled and crushed by hand to separate the minerals without the formation of the large amount of fines that would be produced by machine grinding. The sample, which had been kept at original bed moisture, slacked into fines immediately upon air drying at room temperature. Oven drying was not considered desirable because of the changes effected in both the organic matter and the hydrous minerals during such treatment. Precise quantitative mineralogy was not possible with this lignite because a material balance could not be maintained throughout a separation. The disaggregated sample, all of which passed a 20-mesh screen, was sieved

to − 25 + 50, − 50 + 100, − 100 + 200, − 200 + 325, and − 325 mesh fractions. Samples from each of these sieve fractions were tested radiometrically, dried at 110° C, ashed, analyzed for uranium, and analyzed spectrographically.

The sieve fractions, except for the − 325 fraction, were separated by float-sink in a liquid of 1.7 specific gravity in standard separatory funnels by modifying slightly the procedure reported by Ball (3). The liquid used was a mixture of carbon tetrachloride and bromoform.

Care was necessary to prevent the solution of organic material by the action of the heavy liquids. Carbon tetrachloride and bromoform were satisfactory for heavy-liquid separation, but when such a mixture is used, washing should be done with carbon tetrachloride. On one occasion when acetone was used as the washing agent for about 30 g of mineral-free coal, the acetone filtrate showed immediate darkening, indicating that an extraction had taken place. This was demonstrated when 10 ml of the filtrate was collected in an evaporating dish and evaporated to dryness to yield a resinous brown residue that hardened rapidly. A sample of the acetone filtrate was analyzed, and the uranium content was determined to be 0.00447 mg/100 ml; the total solids in the sample were 0.32 g/100 ml. The uranium content of the solid extract, 0.0014 percent, showed that careful choice of liquids was essential to keep organic extraction to a minimum and to prevent loss of some uranium from the original sample.

The fine sieve fractions offer a special problem in separation. Isolation of clay minerals from quartz was not successful even when −400 mesh material was used. Centrifugation helped somewhat, but quartz-free separates were not obtained.

The individual minerals were isolated by heavy-liquid separation techniques. The difficult separation of gypsum from clay minerals that have about the same specific gravity was greatly simplified by gently heating the clay-gypsum separate under an infrared heat lamp to alter the gypsum to the hemihydrate and to anhydrite. This change of gypsum to minerals of higher specific gravity permits the ready separation of clay minerals in a liquid of specific gravity 2.4.

The sieve fractions of the disaggregated lignite showed no great variation in their analyses (Table 2). The finer fractions generally had a lower ash content and the finest fraction, − 325 mesh, had the highest uranium content. Gypsum, the most abundant mineral, does not crush easily and therefore tends to remain on the coarser sieves.

Although the finer sieve fractions of the bulk lignite have a lower ash content, the reverse is true for the separated organic material with a specific gravity less than 1.7. This is shown in Table 2. The poor separation of minerals from the organic material in the finer fractions is reflected in the ash analyses of the B and C series of samples in this table. Series B consists mainly of organic material; series C mainly of minerals. It should be noted that the separates wth a specific gravity greater than 1.7 were ashed to remove all the organic matter so that the uranium analyses could be made. In sample 1-C, for example, there was little organic matter, and most of the

TABLE 2

ANALYSES, IN PERCENT, OF LIGNITE, SIEVE FRACTIONS, AND SPECIFIC GRAVITY SEPARATES OF SAMPLE FROM MENDENHALL STRIP MINE, HARDING COUNTY, SOUTH DAKOTA

Sample	Mesh	Moisture	eU	Ash	Uranium in ash	Uranium in dry sample
Original lignite		42.0	0.018[1]	32.4	0.12	0.039
Sieved bulk lignite						
1-A	−25+50	25.2	0.016[2]	32.2	0.104	0.033
2-A	−50+100	20.1	0.026[2]	28.8	0.132	0.038
3-A	−100+200	17.5	0.028[2]	27.9	0.120	0.033
4-A	−200+325	15.9	0.026[2]	25.6	0.138	0.035
5-A	−325	13.6	0.027[2]	26.4	0.155	0.041
Sieved separate, specific gravity <1.7 (mainly organic material)						
1-B	−25+50	—	0.025	13.8	0.31	0.043
2-B	−50+100	—	0.020	14.4	0.30	0.043
3-B	−100+200	—	0.021	15.7	0.33	0.052
4-B	−200+325	—	0.023	17.7	0.20	0.035
Sieved separate, specific gravity >1.7 (mainly minerals)						
1-C	−25+50	—	0.021	75.1	0.014	0.011
2-C	−50+100	—	0.033	71.3	0.016	0.011
3-C	−100+200	—	0.039	69.8	0.019	0.013
4-C	−200+325	—	0.041	55.3	0.017	0.009

[1] Percent eU determined on sample with original bed moisture.
[2] Percent eU determined on air dry material.
All other determinations based on samples dried at 110°C.

loss in weight on ashing results from the removal of water from the hydrous minerals.

The mineral separates show a marked radioactive disequilibrium. Although the equivalent uranium [3] content of the mineral separates is generally greater than that of the organic fractions, the uranium content of the mineral separates is only one-fourth that of the organic fraction. The minerals that comprise about 20 percent of the air-dried lignite contain only about 7 percent of the total uranium in the lignite. The organic material, therefore, contains about 93 percent of the total uranium. Sulfate minerals commonly coprecipitate radium sulfate, an extremely insoluble compound, and it is

[3] When samples are measured routinely for total radioactivity by counting techniques in the U. S. Geological Survey, the results are reported, not in terms of radioactivity, but rather as the percent uranium that a sample would contain if all the radioactivity resulted from uranium and its daughter products in equilibrium. This has been termed percent equivalent uranium. A sample with a given percent equivalent uranium may contain this amount of uranium, a fraction of it, or no uranium at all. In the last two cases the balance of the radioactivity will be due to some other disintegrating element such as thorium or radium. Here the chemical and radiometric analyses will not agree.

probable that radium has been selectively concentrated in the sulfates and is the cause of the observed disequilibrium.

Mineral Identification.—The minerals present in the lignite from the Mendenhall strip mine are gypsum, jarosite, quartz, kaolinite, calcite, and a clay mineral—possibly allophane. All the minerals except the clays were easily identified by their optical properties as determined with the polarizing microscope. The gypsum could be recognized in hand specimen; once identified, the jarosite was readily recognized even in minute quantities by its characteristic yellow color. Quartz and calcite were best identified by optical methods because they were almost always present as grains fine enough to pass a 50-mesh screen.

The mineral matter separable by a liquid of specific gravity 1.7 is 20 percent by weight of the air-dried lignite. As previously indicated this could not be a precise determination but was as good a figure as could be obtained with the procedures followed. Starting with lignite of 42.0 percent bed moisture, each of the sieved fractions lost water at a different rate. The moisture of air-dried material ranged from 25.2 percent for $-25+50$ mesh material, to 13.6 percent for -325 mesh material. Oven drying for material to be used for quantitative mineral separation was unsatisfactory because gypsum dehydrated to the hemihydrate and to anhydrite, the characteristics of clay minerals were modified, and even the jarosite lost some water at 110° C.

The average mineral composition for the upper bed of the lignite from the Mendenhall strip mine is as follows:

Gypsum	69 percent
Jarosite	10 percent
Quartz	2 percent
Kaolinite and other clay minerals (mostly "allophane")	19 percent
Calcite	<1 percent

Only trace amounts of other minerals are present.

In the course of tests run to identify the clay minerals by X-ray diffraction, the presence of quartz, calcite, gypsum, jarosite, and kaolinite was confirmed. Excellent X-ray spectrometer graphs for gypsum and other calcium sulfate hydrates were obtained indicating that changes in composition probably took place in the brief time necessary to separate the minerals. Electron micrographs of jarosite from the Menhenhall mine columnar sample (Fig. 1) exhibit the perfect crystallinity of the jarosite, even in single discrete particles less than a micron in size. Hexagonal outlines of rhombohedral plates with well-developed pinacoids, and the pseudo-cubic rhombohedra so characteristic of jarosite are illustrated.

Many differential thermal analyses were made on a clay mineral separated from the lignite. It is thought that this clay may be the mineraloid allophane. The "allophane" from the lignite is a rather anomalous material, and, although it cannot be completely separated from quartz and a small percentage of what is probably kaolinite, its isotropism is definite. This "allophane" has a higher index of refraction than that reported in the literature,

but it is believed that the higher index can be attributed to the presence of a ferric hydrate. Electron micrographs of the material (Fig. 1) show only the irregular outlines of extremely small particles so typical of truly amorphous material; the complete absence of any well-defined recognizable shape makes

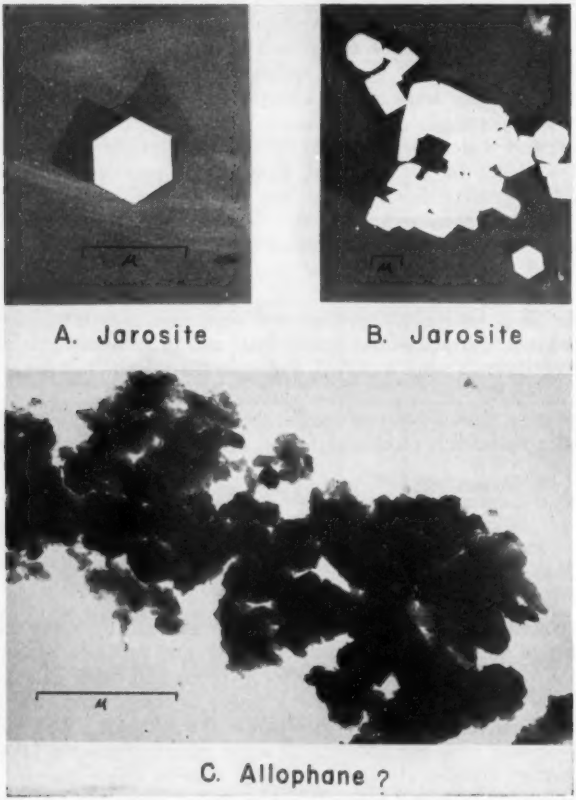


FIG. 1. Electron micrographs prepared by E. J. Dwornik. *A*. Jarosite, chromium shadowed at angle of 32° from two directions 90° apart. *B*. Jarosite, chromium shadowed at angle of 34°. *C*. Allophane (?), unshadowed.

it unlikely that this material is kaolinite or any of the other well-crystallized clays of similar composition. Spectrographic analysis shows that only silicon, aluminum, and iron are present in amounts greater than 1 percent; some of the silicon represents the quartz which could not be separated from the clay.

Because the "allophane" contains some organic material and other minerals, the thermograms for this material were not diagnostic.

This particular clay-mineral separate was found to contain 0.003 percent uranium, which is only about one-fourth that of any aggregate mineral separate, and less uranium than held in any other material separated from the lignite. This fact rules out any appreciable association of uranium with clay minerals.

Alpha-plate Studies.—Six alpha plates (11) of fine-grained material were made—two of the − 165 mesh clay-quartz fraction, two of the − 165 mesh material with specific gravity 2 to 2.4, and two of 80–165 mesh material with specific gravity 2 to 2.4. The material in the specific gravity range 2 to 2.4 was mostly gypsum, clay, and quartz, with some fine grains of jarosite. Very few alpha-particle tracks were observed, but some definitely originated within mineral grains. There was no concentration of alpha-particle tracks, and judging from the track population, the uranium was sparsely disseminated

TABLE 3

ASSOCIATIONS OF ELEMENTS IN ASHED LIGNITE AND ASHED SINK-FLOAT SEPARATES (−25 +50 MESH) FROM A SAMPLE OF THE UPPER BED, MENDENHALL STRIP MINE, HARDING COUNTY, S. DAK. (IN PERCENT)

	Ash	>10	10–1	1–0.1	0.1–0.01	0.01–0.001	0.001–0.0001
Original coal	32.2	Al Si Fe	Ca Mg Na	Mo Ba B	Ti Sr As Mn Zr Ni Co Cr Cu Pb Zn	Ga V Y Sn Sc	Be Yb
Float (1.7 specific gravity)	13.8	Al Fe	Si Na Mg	Ca Mo Ti B Zr Ba Mn	As Cu Sr Ni Co Cr Zn	Ga V Y Sn Sc	Be Yb
Sink (1.7 specific gravity)	75.1	Si	Al Ca Fe	Na Mg Ba	Sr Ti Mo B Cu Mn Pb	Zr Ge Cr Ga V Sn Ni Y	Yb

through the mineral grains and was possibly associated with occluded organic matter. There was no evidence that any of the mineral grains were uranium minerals or contained high concentrations of uranium.

Trace-elements Studies.—A sample of lignite from the Mendenhall strip mine in Harding County, S. Dak., was analyzed spectrographically as were its sink-float separates. These analyses are presented in Table 3.

Lignites have not been studied in as much detail as have bituminous and subbituminous coals, and as a consequence most compilations of coal and coal-ash analyses make little or no reference to lignite (9). Gibson and Selvig (7) made a thorough review of the literature and reported only two analyses of ashed lignite.

The method used in the semiquantitative spectrographic analysis for 68 elements in one exposure of a 10-mg sample was developed by C. L. Waring and C. S. Annell (13) of the Geological Survey. Because the standard plates were prepared with elemental concentrations differing by a factor of

10, the analyses are reported in the percentage ranges listed below:

10 or greater
1–10
0.1–1
0.01–0.1
0.001–0.01
0.0001–0.001

The standard sensitivities for the elements determined by the semiquantitative spectrographic method at the time these analyses were carried out are given in Table 4. Greater sensitivities have now been attained.

Germanium was observed in the mineral separate but was not detected in either the original coal or in the coal separate. This is unusual and may represent an important clue to the geochemical behavior of germanium, which normally is associated with the coal substance (10) rather than with the separable minerals.

TABLE 4

STANDARD SENSITIVITIES FOR THE ELEMENTS IN LIGNITE ASHES DETERMINED BY THE SEMIQUANTITATIVE SPECTROGRAPHIC METHOD (IN PERCENT)

Minor and trace elements

Ag — 0.0001	Ge — 0.001	Sn — 0.01
As — 0.1	La — 0.01	Sr — 0.01
B — 0.001	Li — 0.0001 (0.1)[1]	Ti — 0.001
Ba — 0.0001	Mo — 0.001	U — 0.1
Be — 0.0001	Mn — 0.001	V — 0.01
Co — 0.01	Ni — 0.01	Y — 0.001
Cu — 0.0001	P — 0.1	Yb — 0.0001
Cr — 0.001	Pb — 0.01	Zn — 0.01
Ga — 0.01	Sc — 0.001	Zr — 0.001

Major elements

Al — 0.0001	Fe — 0.001	Na — 0.001 (0.1)[1]
Ca — 0.001	K — 0.01 (1.0)[1]	Si — 0.0001
	Mg — 0.0001	

Sensitivities of elements not detected

Au — 0.01	Ho — 0.01	Rh — 0.01
Bi — 0.001	In — 0.001	Ru — 0.01
Cd — 0.01	Ir — 0.1	Sb — 0.01
Ce — 0.1	Lu — 0.01	Sm — 0.1
Cs — 0.1 (1.0)[1]	Nb — 0.01	Ta — 0.1
Dy — 0.01	Nd — 0.01	Tb — 0.01
Eu — 0.01	Os — 0.1	Te — 0.1
Er — 0.01	Pd — 0.01	Th — 0.1
F — 0.1[2]	Pr — 0.01	Tl — 0.1
Gd — 0.01	Pt — 0.01	Tm — 0.01
Hf — 0.1	Rb — 0.01 (10.0)[1]	W — 0.1
Hg — 0.1	Re — 0.1	

[1] A second exposure is required for the high sensitivity listed. Sensitivity with single exposure is shown in parentheses.

[2] A special exposure is required for the fluorine estimation.

Note: The standard plates are prepared with elemental concentrations differing by a factor of 10; hence, some elements can be detected below the sensitivities listed but not necessarily to the next lower value.

Arsenic, which might be expected to appear in arsenical pyrite, is not detectable in the mineral separate but is concentrated in the coal separate, indicating a possible organo-arsenic association. This is to be expected from the forms of sulfur analysis, Table 1, which shows that pyritic sulfur has been almost completely oxidized to sulfate sulfur. If the arsenic were associated with pyrite, its presence in the coal separate could be accounted for by reaction of the coal substance with oxidized arsenic compounds.

The concentrations of Mo, B, Mn, Be, and Zr in the original coal (Table 3) are not readily explained, but the authors have observed similar concentrations in other coals that have been investigated.

CHEMICAL INVESTIGATIONS

As the mineralogic studies showed that the greater part of the uranium is associated with the organic constituents of the coal, rather than with its minerals, and as studies of the chemical structure of coal (5, 6) indicated that low-grade coals probably have well-developed ion-exchange properties, it was decided to attempt to extract the uranium from the lignites and thus to confirm the hypothesis that the uranium is held by ion exchange. Although the alpha plate studies ruled out the possibility that the uranium might be held in the coal as finely divided discrete mineral grains, the existence of a finely disseminated organo-uranium compound or complex still required consideration.

Extraction Studies.—To determine if uranium is held in lignite in a loose combination, 50 g of bulk lignite from the Mendenhall strip mine was refluxed for two hours with 500 ml of 1 *N* hydrochloric acid. After cooling, the suspension was filtered and the lignite was returned to the flask for a second identical treatment. Each of the two filtrates was evaporated to dryness and, along with the extracted residue, was weighed and analyzed for uranium. The flow sheet for this simple experiment is shown in Figure 2 and related data are given in Table 5. A material balance indicated that most of the uranium in the lignite, 88.5 percent, was extracted by the 1 *N* acid.

The extracts from the coals contain a high percentage of inorganic material. This is reflected by a decrease of 55 percent in the ash content of the original coal (Table 5).

The complete extractability of the uranium from the Mendenhall lignite was demonstrated by treating 80 g of the coal in the Soxhlet extractor with the condensed vapors of boiling 6 *N* hydrochloric acid. Under these conditions of continuous extraction with warm, approximately 6 *N* acid, 98.6 percent of the uranium was removed from the coal in several hours.

The choice of hydrochloric acid for this work was governed by the ease of its recovery through the distillation of its azeotrope. The hydrochloric acid was chosen purely as a source of hydrogen ions. There is no reason to believe that any other acid would not serve equally well for effecting the extraction.

Columnar Extractions.—The results from extraction experiments again pointed to the possible retention of uranium in the coal by ion exchange. An elution experiment was designed to investigate this possibility further.

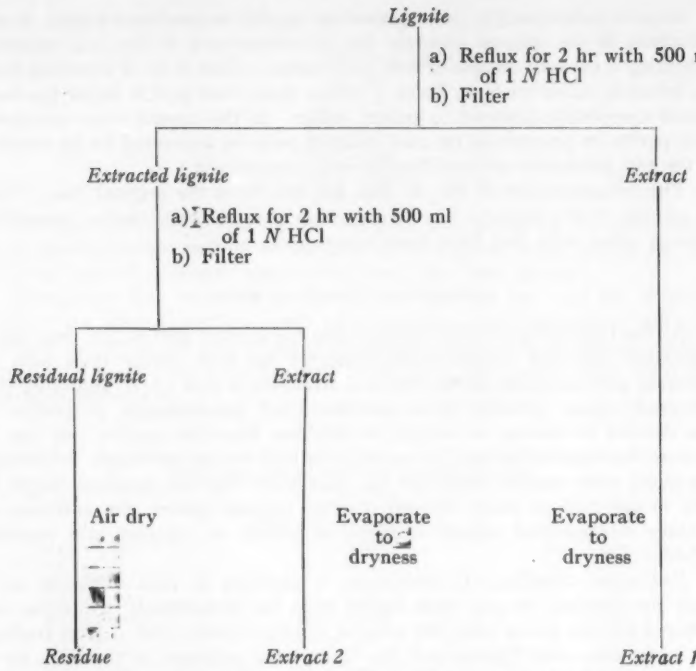


FIG. 2. Extraction of uranium from lignite by 1 *N* hydrochloric acid.

An undried and unground sample of the Mendenhall bulk lignite (49.52 g) was mixed intimately with 12.38 g of a commercial brand of diatomaceous earth. A glass tube was loosely packed with this mixture to form a column 17 × 550 mm. The coal-Celite mixture was supported by a plug of Pyrex wool, and a small glass stopcock was sealed to the base of the column so

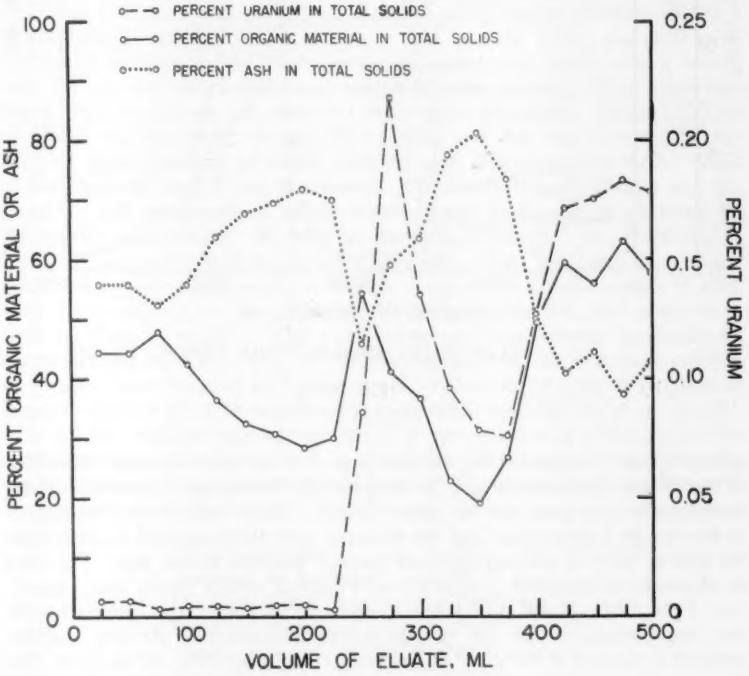
TABLE 5

EXTRACTION OF LIGNITE FROM THE MENDENHALL STRIP MINE WITH 1 *N* HYDROCHLORIC ACID

	1	2	3	4	5	6
	Loss at 105° C (percent)	Ash in dry sample (percent)	Uranium in dry sample (percent)	Uranium in dry ash (percent)	Weight of dry sample (g)	Weight of uranium in dry sample[1] (mg)
Original coal	41.96	32.43	0.039	0.12	29.0	11.3
Extract 1	3.02	59.1	0.083	0.140	10.84	9.0
Extract 2	5.66	32.8	0.096	0.292	1.05	1.0
Residual coal	23.3	14.4	0.0005	0.004	—	—

[1] Calculated from columns 3 and 5.

that the rate of flow of effluent could be adjusted. To attain equilibrium conditions and saturate and wash the column, 200 ml of distilled water was passed through the coal. The rate of flow of the water through the column was increased by connecting a rubber tube between the top of the glass tube and the low pressure side of a reducing valve that was attached to a cylinder of compressed nitrogen. A pressure of 7.5 psi of nitrogen was found to be sufficient to give a reasonable rate of flow. The effluent was collected from the bottom of the column in 25-ml fractions. Following the disappearance of the last of the 200 ml of water at the top of the column, 325 ml of 1 *N* hydrochloric acid was added. The collection of fractions was then continued until 510 ml of effluent had been obtained. The effluent, prior to the break-through of the acid, had a pH of about 2.7; at the break-through the pH dropped to 0.56, the same as that of 1 *N* hydrochloric acid. The water effluent was a light-yellow color and acicular crystals of gypsum, identified



ELUTION OF URANIUM FROM LIGNITE BY 1 N HCl: RATIOS

FIG. 3.

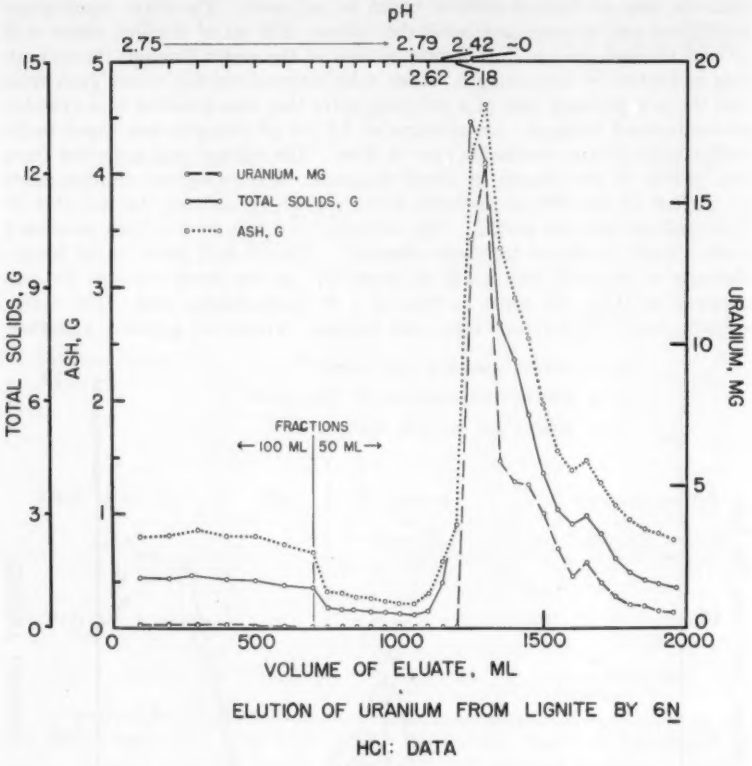


FIG. 4.

microscopically, separated out on standing. At the break-through, the color of the effluent changed abruptly to dark reddish brown, and consecutive fractions then became progressively lighter brown. Each fraction was evaporated to dryness on a steam bath and the residues were then analyzed to determine the loss at 105° C, percent ash, and percent uranium in the ash. The data so obtained are reported graphically in Figure 3, which shows that, regardless of the shape of the curves, the uranium in the ash varies inversely with the total amount of the ash for the series of fractions. As any fraction contains a mixture of inorganic and organic constituents, the curves show that the uranium varies directly with the organic constituents of the fractions.

A small amount of uranium is probably soluble in the water effluent (pH 2.7), but at the break-through of acid the amount of uranium that is eluted increases sharply. The reason for the sharp dip and rise in the curves following the elution of about 350 ml of water and acid is not known. It is

thought that a very irregular acid front combined with some lack of equilibrium in the column because of excessively rapid flow of liquid may have contributed to this feature. Slow attainment of equilibrium was noted in the work described below.

This experimental work indicated that a factor other than ion exchange might account for the association of the uranium with the organic materials: possibly the existence of an organo-uranium compound or complex that is insoluble at pH 2.7 but soluble at pH 0.5.

Continuing on the assumption that a column of uraniferous lignite may be similar to a column of ion-exchange resin on which uranium had been adsorbed, an experiment was designed using the previous technique but replacing the 1 *N* hydrochloric acid by 6 *N* hydrochloric acid. This procedure was used to attempt to reproduce the previous work under more favorable conditions, and to determine if all the uranium could be elutriated just prior to the break-through of the descending acid front.

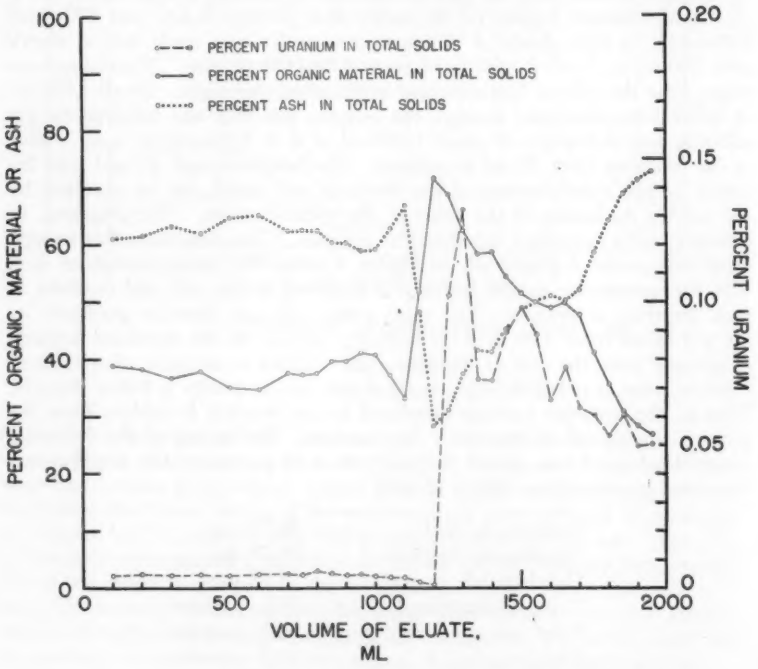
Using a column with an outside diameter of 32 mm, a mixture of 400 g of the Mendenhall lignite (− 50 mesh, 36.6 percent H_2O) and 100 g of Celite-545 (a high grade of diatomaceous earth) was made into a slurry with 800 ml of distilled water and poured into the column. Elutriation was begun after the column had remained undisturbed overnight. In all 1,700 ml of water were elutriated through the column, and this was followed by the addition and elutriation of about 1,000 ml of 6 *N* hydrochloric acid. Most of the fractions were 50 ml in volume. The break-through of acid was detected by pH measurements of the fractions and could also be observed by the sudden darkening of the color at the break-through. The fractions, as obtained, were submitted for chemical analysis. The data from this experiment are presented graphically in Figure 4 where the break-through of acid, with the consequent sudden increase of total dry solids, ash, and uranium in each fraction, is evident. The total solids and ash increase gradually as the pH drops from 2.79 to 2.18, probably because of the increased solution of gypsum from the coal at the lower pH. There is no great elutriation of uranium even at pH 2.18 indicating that the critical acidity is below this pH. That all the uranium was not elutriated in one fraction is evident from the gradual sloping off of the curve for uranium. By means of the following material balance it was shown that only about 75 percent of the uranium was recovered by elutriation with 6 *N* acid.

Uranium in coal	= 88.76 mg
Uranium in fractions	= 66.53 mg
Uranium left in coal	= 13.55 mg
Uranium elutriated	= 75.0 percent
Total uranium recovered	= 86.8 percent
Loss	= 13.2 percent

The data used to compile Figure 4 were recalculated on the basis of the total solid material (both organic and inorganic) elutriated and recovered from each fraction. These recalculated data are plotted in Figure 5. In

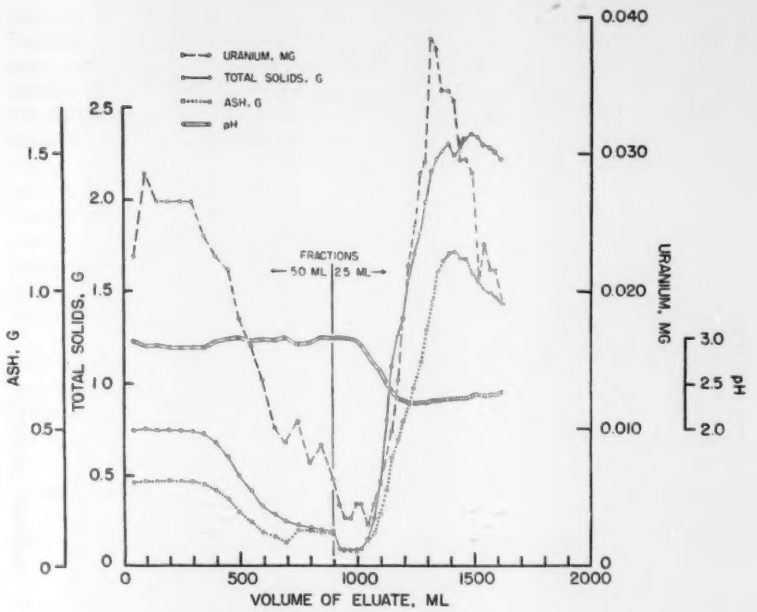
Figure 5 one curve represents the ash content of each fraction; another curve represents the uranium content of each fraction. As the ash represents the inorganic constituents, 100 percent minus percent ash must represent the organic material elutriated from the column by the water or acid during its passage through the coal. Because of the analytical procedure, 100 percent minus percent ash must also include a small amount of water not driven off at 105°C, along with other minor losses that may occur if some inorganic compound decomposes during the ashing procedure. In Figure 5, the acid break-through is accompanied by increase in uranium and a relative decrease in the proportion of inorganic matter in the fraction. From Figures 5 and 3, it is evident that the uranium follows the organic material rather than the inorganic material. Again, therefore, an association between the organic extract and the uranium is observed.

To complete the study of the possible retention of uranium in the coal by ion exchange, the following experiment was carried out. A glass column



ELUTION OF URANIUM FROM LIGNITE BY 6N HCl: RATIOS

FIG. 5.



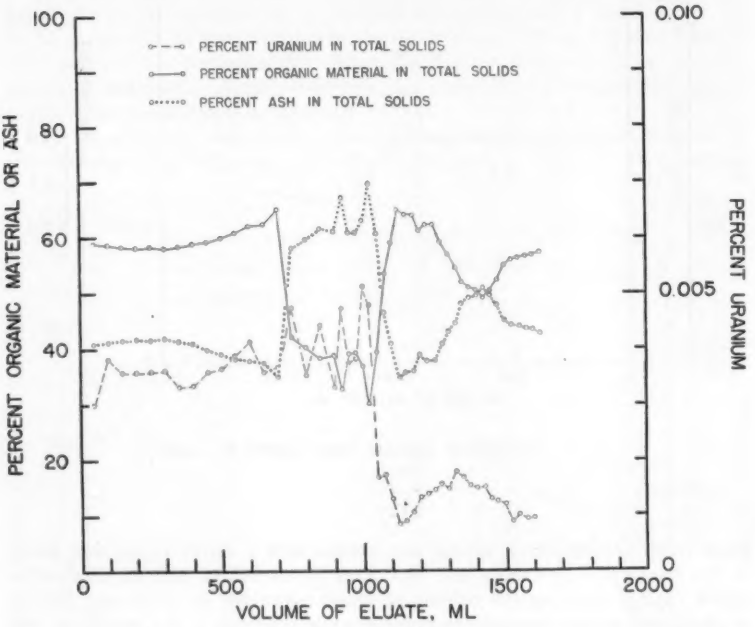
ELUTION OF URANIUM FROM LIGNITE BY $La(NO_3)_3$: DATA

FIG. 6.

made from 32-mm Pyrex tubing was loaded with a slurry containing 200 g of the lignite (− 50 mesh) and 66.7 g of Celite-545 in 500 ml of distilled water. After allowing the column to stand overnight an additional 500 ml of water was passed through the column while fractions of the percolate, first 50 ml and then 25 ml in volume, were taken. Following passage of the water through the coal, 925 ml of a solution containing 100 g/liter of $La(NO_3)_3 \cdot 6H_2O$ was added. Lanthanum was chosen as a displacing ion because of its valence of three and its inertness during the analysis for uranium. As the lanthanum solution had a pH of 4.43, there was no possibility of the removal of uranium from the coal by the solution of an organo-uranium compound or complex. This possibility had existed when hydrochloric acid at a lower pH was used. The lanthanum ion would replace any ion-exchanged uranium or other elements in the coal with its effectiveness purely a function of concentration and valence.

A total of 47 fractions representing 1,275 ml of percolate were removed from the bottom of the column and analyzed. The curves in Figure 6 summarize the analytical data obtained in this experiment, and the curves in

Figure 7 represent, for each fraction, the percent ash and the percent uranium in the total dry solids and, by difference, the percent of "organic material" in the dry solids recovered from each fraction. In order to check this work and also to have a blank determination for comparison a duplicate column was operated simultaneously with only water being percolated through the coal. Within close limits the data for the blank and test columns were similar until the break-through of the lanthanum.



ELUTION OF URANIUM FROM LIGNITE BY $La(NO_3)_3$: RATIOS

FIG. 7.

In Figure 7 the curve showing the elutriation of the uranium is comparatively smooth until the break-through of lanthanum occurs following the collection of 1,000 ml of percolate. The variability in the points of the curve between about 600 and 1,000 ml of percolate is a reflection merely of the size of sample taken for the uranium determination. All these points are within the limits of error of the analytical procedure used. After the percolation of about 1,000 ml of liquid through the column there is a very sharp decrease in the concentration of uranium because of dilution by lanthanum.

That there is no real change in the concentration of elutriated uranium is evident from Figure 6 where no sharp break occurs in the curve at this point. That section of the curve for uranium following the break-through of the lanthanum will be discussed below.

In Figure 7 the curve for ash content of the solid material elutriated from the column is quite regular until 700 ml of water were passed through the coal. At this point, before the addition of lanthanum, there is a sudden and very sharp increase in the ash recovery followed by a leveling off of the curve. This sharp break, which is reproduced exactly in the blank column, resulted when the columns remained overnight at this point during the experiment. The sharp break seems to imply, therefore, that the rate of percolation of water had been too rapid, and that during the period of standing equilibrium conditions were approached.

The sharp and large loss of weight of the solid extracts from the fractions collected at the point where lanthanum breaks through the column probably results from two causes. First, $La(NO_3)_3 \cdot 6H_2O$ decomposes at 126° C. This means that, as lanthanum is collected in the fractions, the nitrate loses its water of crystallization on ashing, but apparently loses only part of this water (if any) on drying at 105° C for 3 hours. Secondly, $La(NO_3)_3$ decomposes at 800° C with the elimination of NO_2 and O_2, which contribute to the loss of weight on ashing (8). Following the break-through of the lanthanum in equilibrium quantity,

$$2La(NO_3)_3 \rightarrow La_2O_3 + 6NO_2 + 11/2\ O_2,$$

the curve for percentage ash should reach a new level and remain reasonably constant.

Those sections of the curves following the break-through of lanthanum are of particular importance and will be considered together. In the curve showing the elutriation of uranium, it is evident that the break-through of lanthanum is accompanied by first a lowering and then an increase in the pH of consecutive fractions. This trend in pH indicates that the coal structure has an ion-exchange capacity that is not saturated. The displacement of hydrogen ions by lanthanum and the subsequent concentration and elutriation of the hydrogen ions results in a simultaneous lowering in the pH of the fractions of percolate so effected. With the lowering of pH it can be seen from Figure 7 that not only does the percentage of uranium in the recovered percolate increase, but also that the percentage of ash increases.

Inasmuch as no appreciable ion exchange of uranium or other elements by lanthanum can be expected until just before or after the break-through of the lanthanum, it is evident that only those portions of the curves in Figures 6 and 7, which represent the removal of more than 1,000 ml of percolate, are significant in this study. Comparison of the elutriation of uranium and inorganic substances beyond this point indicates that the elutriation of uranium is directly related to the displacement of inorganic matter from the column and is inversely related to the displacement of organic material. This result is the opposite of that found when elutriation of uranium was carried out with either 1 *N* or 6 *N* hydrochloric acid in previous studies.

The fact that the uranium is not leached even at a pH as low as 2.18 and the fact that the uranium does not vary directly with the organic content of the percolate indicate that uranium shown in Figure 7 that was displaced after the elutriation of about 1,125 ml of solution was truly ion-exchanged uranium. This experiment indicated that the uranium held in the lignite by ion exchange probably amounts to about 1.2 percent of the total uranium in the lignite.

To check the possible displacement by lanthanum of ion-exchanged elements other than uranium and hydrogen, the ashes from 35 fractions obtained in this experiment were analyzed spectrographically. The data show that none of the following elements is held in the coal by ion exchange: Mn, Sr, Fe, Ni, Co, Be, Mo, Ti, Li, Pb, V, Zr, Cr, Sn, and Mg. There is evidence that the following elements may be held in the coal to some extent by ion exchange: Na, Cu, Zn, Y, Ba, and Si. These last elements are concentrated during the elutriation. It must be remembered that bracketed values (1–10 percent, 0.1–1 percent, 0.01–.1 percent, etc.) are being compared and that the concentration of some elements may not be recognized from the data.

CONSIDERATIONS REGARDING THE INTRODUCTION OF URANIUM

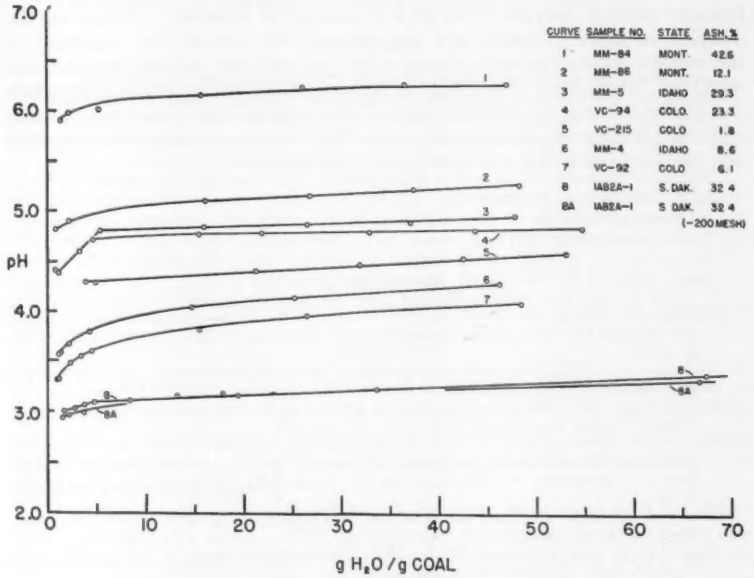
To account for the manner in which uranium may have been introduced into coal by ground water as suggested by Denson and others, it was necessary to have some information regarding the pH of the coal. Eight lignites from Colorado, Idaho, Montana, and South Dakota were chosen for a series of simple studies. Taking 5 g of each sample (− 50 mesh, except as noted) the material was mixed with the minimum amount of water necessary to form a thick paste. The pH of this paste was measured and then more water in known amounts was added and the pH measured after each addition. Several lignites were difficult to wet and the addition of a drop or two of wetting agent (Aerosol, pH 7.2) was necessary. Figure 8 shows that each of the lignites tested had a pH lower than 6.5, even after dilution in the ratio of about 50 parts by weight of water per part of coal. Although the accurate measurement of pH in colloidal solutions or suspensions is difficult, it is obvious that suspension in water of any of the lignites tested results in the formation of a buffered medium. The acidity of each of these coals is undoubtedly dependent upon rank, the nature and quantity of minerals, and history of weathering. The lignite from the Mendenhall strip mine (curves 8 and 8A) is the most acid of the lignites tested. Use of − 200 or − 50 mesh material made little difference in the results of these tests.

It is known that certain alkaline and alkaline-earth uranyl carbonates are soluble in water (1, 2). Typical compounds are: $Na_4(UO_2)(CO_3)_3$, $Na_6(UO_2)_2(CO_3)_5$, and $Mg_2(UO_2)(CO_3)_3$. These compounds are sensitive to acids and break up with the release of carbon dioxide. If such a uranium-bearing solution came into contact with the lignite, a zone of low pH, the following type of reaction would be expected:

$$Na_4(UO_2)(CO_3)_3 + 6HA \rightarrow 4NaA + UO_2A_2 + 3CO_2 + 3H_2O$$

The acids from the lignite represented by HA are unknown in structure and, for the sake of balancing the above equation, are assumed to be monobasic. It is conceivable that a compound such as UO_2A_2 might be insoluble above pH 2.18. This is a suggested process to account for the introduction and retention of the uranium in a coal.

Szalay (12) has recently shown that brown coal will absorb uranium from a solution of potassium uranyl carbonate.



pH CURVES FOR SELECTED LIGNITES

FIG. 8.

DISCUSSION AND CONCLUSIONS

Heavy-liquid separation of minerals has shown that 93 percent of the uranium in a uraniferous lignite is associated with the organic material rather than with the mineral separates. No uranium minerals have to date been isolated from the lignite. The jarosite, quartz, calcite, gypsum, and "allophane" that have been isolated from the coal contain less uranium than does the coal itself.

Uranium can easily be leached from the lignite by dilute acid. Leaching of the coal following beneficiation to remove acid-consuming minerals would result in a concentrate of uranium and also a low-ash coal for fuel or possible chemical use.

Uranium is not held in the coal by ion exchange but seems to be present in the form of organo-uranium complexes or ionic organo-uranium compounds that are soluble at a pH less than 2.18.

It is well known that under certain conditions uranium forms insoluble complexes or compounds with such complex organic substances as tannins and albumins. The type of organic material that retains the uranium in the lignite from the Mendenhall strip mine has not as yet been characterized.

Chemical studies on organo-uranium compounds or complexes are particularly difficult because, first, it is necessary to dissolve or break up the complex in order to isolate the organic material; second, the treatment of the organic substances with strong alkali or acid may change the chemical structure; third, many of the organic substances are also colloidal in structure and can be expected to undergo physical and chemical changes during isolation and characterization; and, fourth, more than one type of organic compound may be responsible for the retention of uranium.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.
Jan. 15, 1955

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BIOGEOCHEMICAL RECONNAISSANCE OF THE ANNIE LAURIE URANIUM PROSPECT, SANTA CRUZ COUNTY, ARIZONA [1]

ROGER Y. ANDERSON AND EDWIN B. KURTZ, JR.

ABSTRACT

A survey of the radioactivity of the vegetation growing on a uranium deposit near Ruby, Arizona, was made in the summer of 1954. The plant ash was analyzed for radioactivity by the alpha scintillation method. The uranium occurs as a zone of irregular pitchblende mineralization in a highly fractured rhyolite porphyry that overlies a series of sandstones, limestones, and shales. The radioactivity of the plants growing over the rhyolite porphyry was twice that of the plants growing over the sedimentary sequence, and plants growing in the zone of pitchblende mineralization were very radioactive. The plant analyses detected another possible pitchblende zone outside the known zone. At the Annie Laurie deposit the method provides an estimate of the amount of uranium mineralization to depths of about 20 feet, depending upon the species used.

INTRODUCTION

MUCH of the emphasis in biogeochemistry has been on exploration, but of equal importance is the evaluation and delineation of known deposits. For evaluation studies a method should be semi-quantitative. The present study describes a semi-quantitative procedure for the evaluation and delineation of a known pitchblende deposit.

Previous biogeochemical studies with uranium have employed the fluorimetric method of analysis. This method may be used to determine very low concentrations of uranium, but it requires a great deal of skill and is likely to give inconsistent results. The present study utilized an alpha scintillation method of analysis, which has the advantage of simplicity and can be carried out by non-technical personnel.

GENERAL GEOLOGY

The Annie Laurie prospect is located 2 miles south of Ruby, in the Oro Blanco mining district of Southern Arizona. The deposit lies in the southwest quarter of Sec. 8, T 23 S, R 11 E, within the Ruby quadrangle of the U. S. Geological Survey.

The Annie Laurie deposit is a small area of irregular pitchblende mineralization on a steep slope on the west side of an arroyo tributary to California Gulch. California Gulch and its tributaries are floored with a series of sandstones, shales, and limey beds. These beds are probably of Mesozoic age and were referred to as part of the Oro Blanco conglomerate by Webb and

[1] Arizona Agricultural Experiment Station Technical Paper No. 353.

Coryell (2). Overlying these rocks, in the immediate area of the deposit, is a nearly horizontal flow of rhyolite porphyry (Fig. 1). The rhyolite porphyry contains rounded quartz phenocrysts and pink orthoclase feldspar in a very fine-grained quartz matrix. The pitchblende is found within lense-shaped zones up to several inches long and less than 1 inch thick in the rhyolite por-

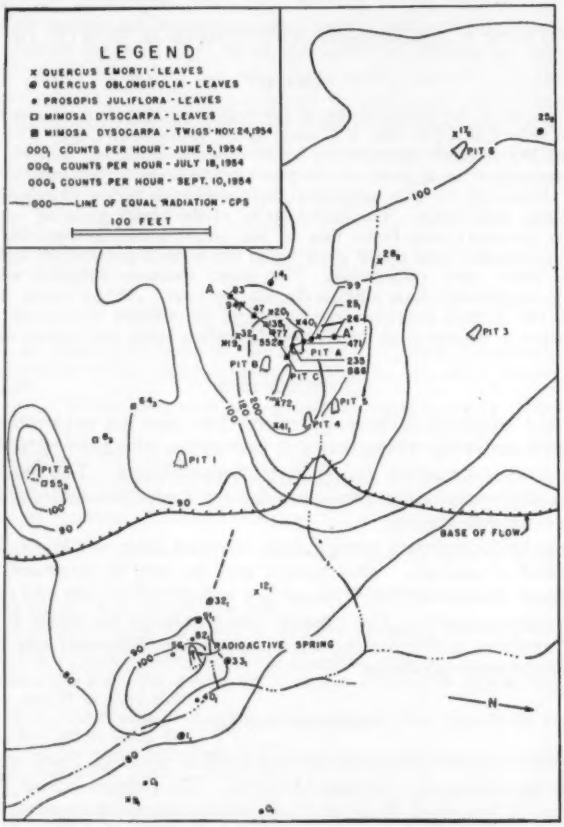

FIG. 1. Radioactivity of the vegetation at the Annie Laurie uranium prospect.

phyry. The latter is highly fractured and recemented with carbonate veinlets. The carbonate veinlets contain minor pyrite, chalcopyrite, sphalerite, galena, and fluorite, but no pitchblende. Pitchblende occurs within 6 feet of the surface in Pit A. According to Wright (3) this occurrence is notably shallow in comparison with most other pitchblende deposits of the western United

States. Secondary uranium minerals are found within a few feet of the ground surface.

Structural control is present in the form of an inferred fault that connects the pitchblende deposit and a spring at the base of the slope. The spring has given rise to a radioactive travertine deposit. The spring has permanent water that apparently flows at a constant rate, since the rate of flow did not visibly change during a 6 month period despite heavy seasonal rainfall in the area. Uranium from the Annie Laurie deposit is probably added to the spring water just before the water emerges. Pitchblende had been mined from pits A and C (Fig. 1), which suggests a localization along the trend of the inferred fault for a short distance.

VEGETATION

The Annie Laurie prospect lies within a portion of the Sonoran desert where the desert grassland-mesquite type of vegetation mingles with the oak woodland and chaparral. The principal trees in the area are two species of evergreen oak, *Quercus emoryi* (Emory oak) and *Quercus oblongifolia* (Mexican blue oak). These two species attain a height of 15 to 20 feet and are distributed at an average interval of about 1 every 50 feet on the hillside containing the deposit. Mesquite, *Prosopis juliflora* var. *velutina,* is about 10 feet high and is found in the washes and on the west-facing slope. The most common shrub, *Mimosa dysocarpa* (velvet pod mimosa), is up to 4 feet tall and occurs at an average interval of 1 every 5 feet. The area has a thick grass cover with more than a dozen species represented.

ORE SAMPLING AND RADIOMETRIC DATA

A radiometric survey (Fig. 1) was made with a scintillation-type counter by Wright (3). Readings were taken at 50-foot intervals with shorter intervals over the mineralized zone. Three anomalies were shown by the survey; one around pit A, another over the radioactive travertine, and a third of slight magnitude over pit 2. At the time of the survey, pit C had not been opened but the dump material from pit A contained pitchblende and the isorad configuration may be distorted around the dump material. The radioactivity over the sedimentary sequence was from 60–70 counts per second (cps), but over the rhyolite porphyry the radioactivity increased to 90–100 cps.

Eight test pits, exclusive of pits A, B, and C, were made by the American Smelting and Refining Company. The results of their analysis and the analyses of the rock in pits A and B are listed in Table 1. Wright (3) states that pit A yielded samples that assayed up to 0.79% U_3O_8, but the mineralization is irregular and bulk sampling of the dump material would be needed for an accurate estimate of the grade. Since the report by Wright (3), pit A has been extended and a new pit, C, has been opened. Some ore has been removed and sold from these two pits.

METHOD

Leaves were analyzed since they generally contain the greatest amount of a given ore element. The analyses of *Mimosa dysocarpa* presented in Figure 2, however, were made on twigs because the samples were collected after the leaves had abscissed. None of the plant samples were washed since there was no difference in the radioactivity of washed and unwashed samples. There had been no mining operations in the immediate area for more than 2 years.

All analyses were made directly on plant ash by the alpha scintillation method. This method is based upon the rate of alpha particle emission from the ash. Finely ground plant material was incinerated in a crucible until a white ash was obtained. The plant ash was placed as a thick source (1 mm)

TABLE 1

SUMMARY OF ORE SAMPLING RESULTS (FROM WRIGHT, 3)

Location	Type of Sample	$\%U_3O_8$
Pit A	6-ft. chip channel cut—south wall	tr.
	5-ft. chip channel cut—west wall	0.63
	3-ft. chip channel cut—north wall	tr.
	1-ft. chip channel cut—west wall	0.006
	Grab	0.40
Pit B	8-ft. chip channel cut	0.013
Pit No. 1	7-ft. chip channel cut	nil
	Grab	tr.
2	4-ft. chip channel cut	nil
	Grab	nil
3	4-ft. chip channel cut	nil
	Grab	tr.
4	5-ft. chip channel cut	nil
	Grab	tr.
5	11-ft. chip channel cut	nil
	Grab	nil
6	10-ft. chip channel cut	nil
7	Grab	tr.
8	Grab	tr.

in a 45.5 mm diameter planchet. The planchet was placed at a distance of 1 mm from the silver-activated zinc sulfide phosphor at the end of an R.C.A. 5819 photomultiplier tube. Pulses from the photomultiplier tube were counted by a scaler. The background for the system was 6 counts per hour and results are expressed in counts per hour (cph) above background for the geometry stated above. The method is similar in principle to that described by Kulp et al. (1). It cannot distinguish between uranium, thorium, and their decay products, but this was not a serious disadvantage because the present study utilized a known uranium deposit.

RESULTS

Oaks were used for general reconnaissance because they have a deep root system and are well distributed over the hillside of the deposit. The ash

from oaks growing over the sedimentary sequence, where the radiometric survey (Wright, 3) showed a radioactivity of 60–70 cps, yielded from 1–10 cph (Fig. 1). Several mesquite trees in this area showed no increase over background. The increased radioactivity of the rhyolite porphyry (90–100 cps) was reflected in the vegetation. Here the radioactivity of the oaks increased to 20–30 cph. The radioactivity of the vegetation markedly increased over the zone of pitchblende mineralization and the radioactive spring. The oak near the spring that yielded the highest count is about twice the size of other oaks in the area and probably derives much of its moisture from the spring.

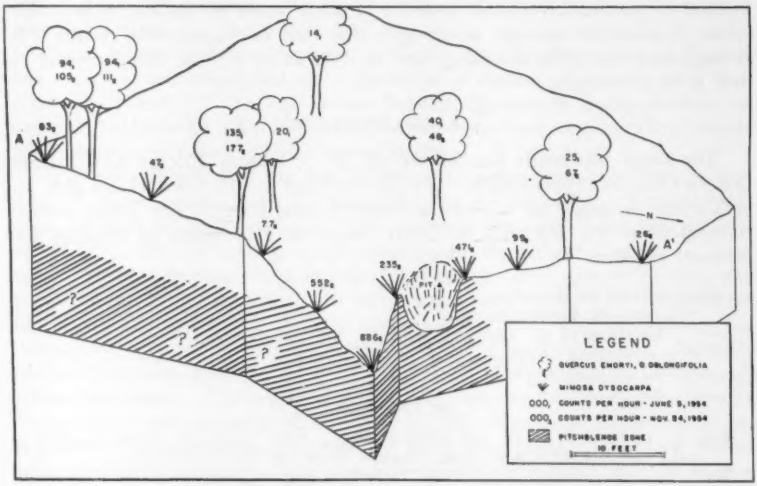

FIG. 2. Cross section of the Annie Laurie uranium prospect to show suspected pitchblende zone. Section A-A′ from Figure 1.

According to the oak analyses, the greatest amount of pitchblende mineralization would be about 30 feet southwest of pit A (Fig. 2), but unfortunately there are no oaks growing over pit A for comparison. Mimosas from near the center of the pitchblende zone were very radioactive. However, mimosas growing under the oaks that were the most radioactive had nearly normal radioactivity. Apparently the roots of oak and mimosa sample different depths and the ore under the most radioactive oaks is at a greater depth than at Pit A. Since the deposit is on a steep hillside, the pitchblende zone, if projected under these oaks, would be nearly horizontal. The alignment of the most radioactive oaks suggests that the suspected pitchblende zone has a narrow linear trend.

CONCLUSIONS

The results of the biogeochemical reconnaissance are in close agreement with earlier ore sampling and radiometric surveys. All three indicate that the pitchblende is limited in extent. The plant sampling data indicate a possible extension of the pitchblende southwest from pit A. The plant analyses provide a rough estimate of the amount of pitchblende mineralization at various depths, depending upon the development and depth of the root system. The alpha scintillation method proved to be adequate, at least for deposits of this type.

The value of plant analysis for uranium lies somewhere between a radiometric survey and the analysis of rock from drill holes or test pits. The method is particularly suited to areas of slope wash or shallow overburden where radiometric surveys would give distorted or inconsistent results. It is suggested that plant sampling data be used as an aid for the placement of drill holes or test pits.

ACKNOWLEDGEMENTS

The study was made possible by the U. S. Atomic Energy Commission Contract No. AT(11–1)–278. We are indebted to Mr. John H. Bright, Jr. of Tucson, Arizona, for use of the Annie Laurie claim. The senior author is indebted to the Maxwell N. Short Memorial Fellowship in Geology for personal expenses.

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Feb. 4, 1955

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DISCUSSION

WIDESPREAD OCCURRENCE AND CHARACTER OF URANINITE IN THE TRIASSIC AND JURASSIC SEDIMENTS OF THE COLORADO PLATEAU

Sir: In the above instructive paper the authors touch, at some length, on the association of uranium mineralization with carbonatized plant fragments and "asphaltic" materials. These two aspects of uranium association have long puzzled me.

Quite extensive field experience in the uranium-bearing areas of Canada has made me quite skeptical as to the value of carbon (graphite) as a uranium precipitant. In the well-known Beaverlodge area of Saskatchewan, for example, widespread graphitic quartzites are completely unmineralized beside well mineralized non-graphitic "mafic" rocks.

But while skeptical of the role of carbon as a significant associate of uranium, I have become much impressed by the obvious affinity between uranium minerals and hydrocarbons. The uranium-bearing hydrocarbon mixture called "thucolite" is quite generally distributed throughout Canada. I have seen it present in rock types including pegmatite dikes, granite masses, and sediments of Proterozoic age. In many cases seen by me (the most recent being generous amounts in the new Algoma-Blind River field of Ontario) the "thucolite" appears as a fresh-looking crustation lining oxidized, obviously leached fractures through which, in all likelihood, methane-laden groundwaters circulated. The evidence seen by me supports the theory advanced by Vernardsky [1] and quoted by C. F. Davidson, that "thucolite" could well be the product of polymerization of methane or other natural gases in ground waters by alpha-radiation from a uranium mineral. This suggests that the hydrocarbon was the latest migrating fraction and the uranium fraction may have moved little, if at all, since its first deposition. I have wondered, since a recent visit to the Plateau area, if the Plateau "asphaltites" may not have experienced an origin similar to that of the Canadian "thucolites" mentioned. In a petroliferous area such as the Plateau there would be no lack of migrating gaseous hydrocarbons.

As regards the influence of carbonatized fragments, I view a process just the opposite to that above-described. I suggest that the active agent in the coalified wood fragments is not the carbon but the hydrocarbon fraction (resin) once present. The efficacy of resins in precipitating uranium is now well known. If this theory is valid then it follows, contrary to the origin of "thucolite" (and asphaltites ?), that the uranium was the latest migrating fraction. The authors noted a somewhat selective replacement of the cell walls of coalified fragments by uraninite as opposed to replacement of the cell

[1] Vernardsky, W., Les problèmes de la radiogeologie. Paris, 1935.

body by pyrite. It would be interesting to learn how this mineral distribution compares with the distribution of resin in the wood cell structure.

TECHNICAL MINE CONSULTANTS LTD.,
TORONTO, ONTARIO, CANADA,
July 7, 1954

FRANC. R. JOUBIN

URANINITE IN THE COLORADO PLATEAU

Sir: The writer respectfully wishes to supplement the record relating to the reported discovery in March 1950 of uraninite in the sandstones of the Colorado Plateau as set forth by Messrs. Rosenzweig, Gruner, and Gardiner in their article, "Widespread Occurrence and Character of Uraninite in the Triassic and Jurassic Sediments of the Colorado Plateau," published in the June–July 1954 issue of ECONOMIC GEOLOGY, and as especially described in the bibliographic reference No. 2—Gruner, J. W., March 1950, Some minerals of the Happy Jack mine: Second Progress Report, U. S. Atomic Energy Commission, p. 1.

On July 29, 1947, while making a routine inspection trip in the interests of the Atomic Energy Commission, the writer visited the Happy Jack claim and examined with a hand lens the massive, partly-oxidized sulphide ore then available on the claim. The examination showed that the ore contained chalcopyrite, bornite, chalcocite, malachite, azurite, chrysocolla, pyrite, hematite, limonite, meta-torbernite, tyuyamunite, autunite, and a blackish mineral which was thought to be pitchblende. A specimen of the ore selected for laboratory study was subsequently lost in handling during the remainder of the field trip; consequently, only the possible presence of uraninite was mentioned in the report on the trip. This report, dated September 9, 1947, recommended that the sulphide mineralization be studied intensively for the possible presence of hypogene pitchblende inasmuch as it might have some bearing on the origin of the carnotite deposits in the Salt Wash sandstone.

The mineralogical laboratory of the Atomic Energy Commission, in New York, N. Y., was also alerted to the possible importance of the Happy Jack sulphide ore. In April 1948 a shipment of the ore was received at the laboratory, and Mrs. Muriel Mathez, then in charge of the laboratory, recognized the black mineral that was thought to be pitchblende. A sample of the mineral was prepared and submitted informally to the U. S. Geological Survey with the oral request that it be X-rayed to verify the tentative identification of pitchblende. In a letter dated July 25, 1948, based on a laboratory report dated July 19, 1948, which is on file in the laboratory of the Geological Survey at the Naval Gun Factory in Washington, D. C., Mr. John C. Rabbitt, of the Geological Survey, notified the Atomic Energy Commission that the black mineral was pitchblende. Thus, this verification of the presence of pitchblende in the sandstones of the Happy Jack mine apparently antedates by one and one-half years the March 1950 reported discovery.

1053, 26 ST. S.,
ARLINGTON, VA.,
July 22, 1954

GEORGE C. SELFRIDGE

REVIEWS

Uranium, Where It Is and How to Find It. By P. D. Proctor, E. P. Hyatt, and K. C. Bullock. Pp. 85; figs. 24; tbls. 4. Eagle Rock Publishers, Box 1581, Salt Lake City, Utah. $2.00 paper cover. $2.50 hardbound cover.

The above three authors at the time of writing of this book were all faculty members of the Department of Geology, Brigham Young University, Provo, Utah. They state in the preface to their book that, "The need for a non-technical and usable guide in uranium prospecting has been apparent for some time. Though a few books have been issued as 'prospecting guides,' none of these appears to have given more than a few cursory remarks on mineralogy, Geiger counters, and some technicalities of the law in regards to claim staking. As far as could be ascertained, no direct and logical approach to the task of training an individual to be an effective prospector has been made. This book is written to overcome some of these deficiencies, and should be of considerable interest to those persons who are interested in uranium, its occurrence, known distribution, and potential areas of undiscovered deposits."

The book, bound in an appropriate canary-yellow carnotite colored cover, was written for the layman. Technical terms are used but in a readily understandable manner. The concise and condensed chapters should prove to be highly illuminating and interesting reading for the lay reader.

The book includes fundamental information on field clothes and equipment (including radiation equipment), availability and information on the various types of maps, how to locate uranium claims, and a simplified mineral identification table (to be used for the recognition of the more common uranium and thorium minerals). The various types of uranium deposits are described in a cursory manner followed by the longest chapter of the book entitled, "Where to Find Uranium, or Try the Crystal Ball." The chapter, however, might better be entitled, "Where Uranium Has Been Found, or Hunt for Elephants in Elephant Country," since it consists of condensed descriptions of many of the known deposits in the United States. The descriptions are further explained by numerous simplified geologic maps that should be easily understood by the layman.

Because of the present great interest in the topic of uranium (and the thoughts of "easy-money" to be thereby acquired), this book should do much to whet the intellectual appetite of the layman in the extremely interesting but rather ignored field of geology. The geologist himself will learn little from this book but when inquiries are received pertaining to uranium, the geologist will not only save time for himself but will perform a service for the profession and the inquirer if he will refer the inquirer to this book.

M. LeRoy Jensen

Yale University,
New Haven, Conn.
Nov. 3, 1954

The Nation Looks at its Resources. HENRY JARRETT, Editor. Pp. 417. Resources for the Future, Inc., Washington, D. C., 1954. Price $5.00.

Resources for the Future called a "Mid-Century Conference on Resources for the Future" in Washington, D. C., on December 2, 3, and 4, 1953. It was attended by 1,600 invited guests who sought to relate issues of resources that will be before the people of the United States during the next 25 years and beyond. It was intended that the conference would not develop a proposed program for resources, or recommend anything, but rather to arrive at a better understanding of the various problems. This volume is the result of that conference.

At the Conference there was an introduction by R. G. Gustavson followed by two key addresses by President Eisenhower and Lewis W. Douglas (the Chairman). There were four papers, by R. D. Calkins, James Boyd, T. W. Schultz, and Earl P. Stevensen. There were two after dinner speeches on the public lands by R. W. Sawyer and Wesley A. D'Ewart, and three on "How Much Should we Depend on Foreign Resources" by Andrew Fletcher, Charles P. Taft, and Robert Garner. These are all recorded in the volume. The rest of the conference consisted of section and subsection meetings, presided over by chairmen, who after introducing the subjects of discussion threw the meetings open for discussion. The section topics were: 1) Competing Demands for the Use of Lands; 2) Utilization and Development of Land Resources; 3) Water Resource Problems; 4) Domestic Problems of Nonfuel Minerals; 5) Energy Resource Problems; 6) U. S. Concern with World Resources; 7) Problems in Resources Research; 8) Patterns of Cooperation.

Each of these sections was subdivided into two or more subsections for convenience of discussion. The main part of this volume records the discussion at the subsection meetings, followed by a summary of the discussions by the section chairmen. An appendix carries an editorial on how the conference was formed and how the volume was prepared, a list of registrants, an index to speakers, and a guide to principal subjects. Some 5,000 pages of proceedings were taken and this volume represents less than 1,000 of them.

The Editor's preface points out that from the mass of material and diversity of views, three significant themes recur in the discussions: 1) the need of research; 2) the need to disseminate knowledge more widely through education, and 3) the need to apply knowledge more widely through cooperation.

The volume assembles a mass of thought and data on the different subjects discussed, which should prove of great value in the spread of knowledge and planning for the future.

ALAN M. BATEMAN

The Origin and History of the Earth. By R. T. WALKER and W. J. WALKER. Pp. 244; pls. 20; figs. 53. Walker Corp., Colorado Springs, Colo. 1954. Price $5.00.

A subject so fundamental and comprehensive as indicated by the title of this book, would need, one might think, a battery of high powered astronomers, physicists, and structural geologists to undertake its solution. But it has bravely been undertaken by two economic geologists with fifty years experience in mining districts. Their answer, in a nutshell, is that the Earth instead of being a shrinking body is just the reverse, due to an expanding mass at the center of the Earth, caused by the disintegration of heavy atoms ("Q-atoms") of the nucleus into simpler and bulky atoms.

The authors first consider the constitution of the Universe, then of the solar system, and of the Earth. This is followed by chapters on The Cause of Vulcanism and Orogeny, The Phenomena of Vulcanism and Orogeny, and The History of the Earth. The earlier chapters point to the causes of volcanism and orogeny, upon which their new hypothesis consists. Many excellent diagrams of structural geological features are given in support of expansion from within.

The authors have fearlessly embarked upon a field of thought that is full of controversy and conflicting opinions, against which their proposed hypothesis will have to stand up. In their discussion of the age of the earth by radioactive measurements they point out some of the difficulties encountered in the utilization of lead isotopes but have apparently overlooked the more recent refined data available. They assign 1 billion years to the star stage of the earth, ½ billion to the "gaseous" and "liquid" divisions, 400,000,000 years to the "pre-aqueous" and "aqueous" subdivisions, and 95,000,000 years from the Archeozoic to the Cenozoic, with another 5,000,000 years from the "present time to its end," or a total of 2 billion years for the whole span. These figures are in strong contrast to modern age figures, which give measurements of around 3 billion years for Precambrian rocks! The list of references given appear to have overlooked the more recent books.

Geology of Petroleum. By A. I. LEVORSEN. Pp. 703; figs. 327. W. H. Freeman and Co., San Francisco, 1954. Price, $8.00.

This long-awaited book by the outstanding petroleum geologist makes the fifth of a group of text books on petroleum geology that have made their appearance in recent years. This book has a different approach and emphasis. It is intended primarily for students with prerequisite courses in geology, and for petroleum geologists engaged in active exploration for oil and gas. The practical and practicing phase is emphasized throughout, and it comes from the pen of a man broadly experienced in such matters.

The book is divided into four parts with 15 chapters. Part I, following an introduction and summary, takes up the occurrence of petroleum, with surface and subsurface occurrences, geographic location, and geologic age. In Part II, The Reservoir, the author jumps right into reservoir rocks, pore space, and traps. Part III, The Petroleum Pool, deals with reservoir fluids, reservoir conditions and reservoir mechanics. Not until Part IV, under Geologic History, is the student introduced to the origin and migration and accumulation of petroleum, which appears as a somewhat back-sided arrangement. This same part carries three additional chapters on subsurface geology, the petroleum province, and the petroleum prospect. An appendix gives a useful glossary of petroleum exploration, abbreviations used on logs, and gravity and scout tables, and pipe capacities.

A pleasing feature of the book is the lack of long descriptions of individual fields, which usually make tiresome reading to the student. Some descriptive material is neatly interwoven into the discussions of subjects, and most of it is carried by abundant and excellent illustrations.

The arrangement of the book is not well suited to the desires of most teachers, but they in teaching can easily start at the back and later jump to the front.

Of the five leading text books in petroleum geology this one stands foremost, and as a reference book to practicing exploration geologists it should prove invaluable.

Minerals in World Industry. By WALTER H. VOSKUIL. Pp. 324; figs. 26. McGraw-Hill Book Co., New York, 1955. Price, $5.75.

The author is Mineral Economist of the Illinois Geological Survey and Professor of Mineral Economics at the University of Illinois. He is therefore well suited to be the author of a book carrying this title.

The book is concerned chiefly with the part played by minerals in economic productivity and in maintaining high living standards. He also presents the thesis that minerals have played an emphatic role in the development of a distinctive American culture due to the exceptionally high standards of living enjoyed by a large part of the population. The author covers also the international political aspects of mineral resources and in the last two chapters discusses the problems of the United States in obtaining mineral supplies for its industry. The resources and requirements of other major nations are also discussed.

The 27 chapters deal with mineral economy, steel empires, iron in the different continents, iron alloys, coal, petroleum and gas in different continents, copper, lead and zinc, light metals, building and fertilizer minerals, and minor minerals.

In the case of the metals, such as copper, there are given brief statements of the relation of copper to the mineral economy, resources in the United States (¼ page) and elsewhere, secondary copper, statistics of world reserves and ownership (much out of date), political and commercial control (not quite correct), and the copper position of the United States in relation to other copper-producing countries, followed by a very brief selected bibliography that is so selected it leaves out some of the important ones. And those included are unfortunately not all free from errors—M. Sengier of Katanga fame might be aghast to read his reference as: "Edgar B. Senger: 'Katanza's Mineral Empire Based on Mining Metals.'"

The book is well balanced and gives a bird's-eye picture of the occurrence, production and economics of the various minerals covered. It should prove helpful as a reference book in geography.

Nuclear Geology. Edited by HENRY FAUL. Pp. 414. John Wiley and Sons, Inc., New York, N. Y., 1954. Price $7.00.

Nuclear geology (also known as isotope geology) is now firmly established as another important subdivision of geology. The subject is of fundamental importance to all students of geology regardless of their specialty because, as stated in the preface, geologists may "find information in these pages that will be of use to them in the solution of problems of their particular interest, *perhaps by methods they have never tried before.*" (italics mine)

Through the efforts of Henry Faul, U. S. Geological Survey (now at Institute de Physique du Globe at Strasbourg, France, as a Fulbright recipient), a series of authoritative papers have been compiled to form this book. The waiver of all royalties is reflected in the moderate price of the text. As stated in the preface, "The book begins with a simple introduction to nuclear physics, actually little more than an animated glossary, followed by an outline of the more important techniques. The occurrence of radioactive elements in rocks and oceans is discussed, and thermal, physical, and chemical effects of radioactivity are considered. One chapter outlines the nuclear methods of geophysical exploration and well logging, and another, a fairly long one, delves in some detail into techniques and results of absolute age determination. The [author of the] last chapter discusses the ultimate in geologic problems, the origin of the Earth."

Some of the papers are excellent review articles, others are rather short but

concise, and a very few are somewhat abortive. The editor has done well in attempts to bridge gaps and maintain a train of thought through the book, although this was an almost impossible task because the list of contributors exceeded two dozen besides the fact that several manuscripts that were promised were never delivered. This latter fact may be the explanation for the omission of a few important topics that one would expect to be included in *Nuclear Geology; e.g.*, the application of radioactive tracers as aids in geologic problems, such as aids in laboratory investigations on solid diffusion rates and the mechanism of replacement. Furthermore, the extremely interesting and important topic of natural variations in stable isotopic abundances is omitted with the stark explanation that "it is fully covered in two forthcoming volumes."

Even though there is much to be said for the symposium style of textbooks (reference texts especially) during this age of increasing specialization, the single authorial or oligauthorial textbook may still prove to be best because of uniform style, overall consistency, and broad complete coverage of all pertinent topics. Nevertheless, I recommend *Nuclear Geology* to all geologists who wish to remain abreast of their colleagues in their understanding of some of the more recent techniques and advances within their profession.

M. L. JENSEN

BOOKS RECEIVED

FRANK G. LESURE

U. S. Geological Survey—Washington, D. C., 1953

Prof. Paper 228. Geology and Geography of the Henry Mountains Region, Utah. CHARLES B. HUNT, assisted by PAUL AVERITT and RALPH L. MILLER. Pp. 234; pls. 22; figs. 116; tbls. 9. Price $6.25. *Well-illustrated, detailed study of classic area of geology—Includes economic geography, stratigraphy, structure, forms of igneous intrusions, petrography of igneous rock, physical geography and resources. Includes colored geologic maps and excellent isometric fence diagrams of intrusions.*

Prof. Paper 260-E, F, G. Bikini and Nearby Atolls, Part 2. Oceanography (biologic). (E) Biologic Economy of Coral Reefs. MARSTON C. SARGENT and THOMAS S. AUSTIN. **(F) Plankton of Northern Marshall Islands.** MARTIN W. JOHNSON. **(G) Recent Brachiopods.** G. A. COOPER. Pp. 293–318; pls. 2; figs. 16; tbls. 6. Price 60 cts.

Prof. Paper 260-Q. Marine Annelids From the Northern Marshall Islands. OLGA HARTMAN. Pp. 619–644; figs. 10. Price 25 cts.

Prof. Paper 264-B. Additions to the Fauna of the Raritan Formation (Cenomanian) of New Jersey. LLOYD WILLIAM STEPHENSON. Pp. 25–44; pls. 3. Price 70 cts.

Prof. Paper 264-C. Pliocene Echinoids from Okinawa. C. WYTHE COOKE. Pp. 45–54; pls. 4. Price 20 cts.

Prof. Paper 269. Water-Loss Investigations: Lake Hefner Studies, Technical Report. Pp. 158; figs. 101; tbls. 29. Price $1.75. *Reprint of Geological Survey Circular 229.*

Prof. Paper 270. Water-Loss Investigations: Lake Hefner Studies, Base Data Report. Pp. 300; figs. 6; tbls. 19. Price $1.75.

Bull. 989-D. Geology of the Eastern Part of the Alaska Range and Adjacent Area. FRED H. MOFFIT. Pp. 65–218; pls. 2; figs. 23. Price $1.25. *Summation*

of geological knowledge of region, gained in more than 40 years of exploration and investigation. Includes stratigraphy, structure, economic geology. Colored geologic map scale 1:250,000.

Bull. 989-E. Geology of the Prince William Sound Region, Alaska. FRED H. MOFFIT. Pp. 225–310; pl. 1; figs. 28. Price $1.25. *Includes colored geologic map scale 1:250,000.*

Bull. 989-F. Effect of Permafrost on Cultivated Fields, Fairbanks Area, Alaska. TROY L. PEWE. Pp. 315–351; pl. 1; figs. 16; tbls. 2. Price 55 cts.

Bull. 990. Geology and Oil Resources of the Jonesville District, Lee County, Virginia. RALPH L. MILLER and WILLIAM P. BROSGE. Pp. 240; pls. 8; figs. 35; tbls. 3. Price $2.75.

Bull. 996-C. Pleistocene and Recent Deposits in the Denver Area, Colorado. CHARLES B. HUNT. Pp. 91–140; pls. 4; figs. 10. Price $1.00.

Bull. 1009-A. Uranophane at Silver Cliff Mine Lusk, Wyoming. V. R. WILMARTH and D. H. JOHNSON. Pp. 12, pls. 2; figs. 1; tbl. 1. Price 40 cts.

Bull. 1009-B. Identification and Occurrence of Uranium and Vanadium Minerals from the Colorado Plateaus. A. D. WEEKS and M. E. THOMPSON. Pp. 13–62; tbls. 2. Price 25 cts. *Description of physical properties, X-ray data and some chemical and spectrographic analyses of 48 uranium and vanadium minerals.*

Bull. 1009-C. Radioactive Deposits of Nevada. T. G. LOVERING. Pp. 63–106; figs. 7; tbls. 8. Price 20 cts. *Study of 25 occurrences of radioactive rocks; 4 deposits showed uranium ore reserves.*

Bull. 1009-D. Further Studies of the Distribution of Uranium in Rich Phosphate Beds of the Phosphoria Formation. M. E. THOMPSON. Pp. 107–123; figs. 10; tbls. 3. Price 15 cts.

Bull. 1015-A. Fluorspar Deposits Near Meyers Cove, Lemhi County, Idaho. D. C. Cox. Pp. 21; pls. 5; fig. 1; tbl. 1. Price $1.25. *Deposits located in Gravel Range mining district of Salmon River Mountains.*

Bull. 1015-B. Niobium (Columbium) and Titanium at Magnet Cove and Potash Sulphur Springs, Arkansas. V. C. FRYKLUND, JR., R. S. HARNER, and E. P. KAISER. Pp. 23–57; pl. 1; figs. 11; tbls. 12. Price 35 cts.

Bull. 1018. Bibliography of the Geology of the Western Phosphate Field. ROBERT A. HARRIS, DAVID F. DAVIDSON and BERTHA P. ARNOLD. Pp. 89. Price 30 cts.

Bull. 1022-C. Geophysical Abstracts 158, July-September, 1954. MARY C. RABBITT, DOROTHY B. VITALIANO, S. T. VESSELOWSKY and others. Pp. 135–203. Price 25 cts. *Abstract numbers 158–1 to 158–227.*

Water-sup. Paper 1137-I. Summary of Floods in the United States During 1950. J. V. B. WELLS. Pp. 957–991; figs. 2. Price 20 cts.

Water-sup. Paper 1186. Quality of Surface Waters of the United States 1950. Parts 1–4. North Atlantic Slope Basins to St. Lawrence River Basin. S. K. LOVE. Pp. 331; fig. 1. Price $1.50.

Water-sup. Paper 1188. Quality of Surface Waters of the United States 1950. Parts 7–8. Lower Mississippi River Basin and Western Gulf of Mexico Basins. S. K. LOVE. Pp. 446; fig. 1. Price $1.50.

Water-sup. Paper 1191. Water Levels and Artesian Pressures in Observation Wells in the United States in 1951. Part 1. Northeastern States. A. N. SAYRE. Pp. 382; figs. 31. Price $1.25.

Water-sup. Paper 1246. Surface Water Supply of the United States 1952. J. V. B. WELLS. Pp. 358; figs. 3. Price $1.25.

Water-sup. Paper 1299. The Industrial Utility of Public Water Supplies in the United States, 1952. Part 1. States East of the Mississippi River. Pp. 639; pls. 5; figs. 3; tbls. 20. Price $2.25. **Part 2. States West of the Mississippi River.** Pp. 462; lps. 5; figs. 3; tbls. 20. Price $1.75. E. W. LOHR and S. K. LOVE. *Part 1 includes data on 819 cities and Part 2 on 416 cities. Lists population, ownership, source and treatment of water supply, storage facilities and chemical analyses.*

Water-sup. Paper 1301. Compilation of Records of Surface Waters of the United States through September 1950. J. V. B. WELLS. Pp. 380; pl. 1; figs. 2. Price $1.75.

Minerals Yearbook—Fuels, Volume II. Bureau of Mines Staff. Pp. 450. U. S. Government Printing Office, Washington, D. C. Price $2.25 (cloth). *Beginning of 3-volume coverage—Vol. I to cover metallic and nonmetallic minerals exclusive of fuels; Vol. II mineral fuels; and Vol. III regional review by State and Territory. Vol. II contains general review, statistical summary and employment-injury presentation of fuel industry; chapters on each mineral-fuel.*

Minerals Yearbook, 1951. U. S. BUR. OF MINES. Pp. 1694. Supt. of Documents, U. S. Govt. Printing Office, P. N. 68221, Washington, D. C., 1954. Price $5.25. *90 chapters summarizing U. S. mineral activity during 1951; same arrangement as formerly. The 1952 Yearbook will appear in 3 Volumes.*

Coshocton-Type Runoff Samplers, Laboratory Investigations. DONALD A. PARSONS. Pp. 16; figs. 12. U. S. Dept. of Agric., Soil Conserv. Ser., Washington, D. C. *Operation, evaluation and design of sampler for studying effect of runoff and soil erosion on land use.*

U. S. Atomic Energy Commission, Oak Ridge, Tennessee. 1954. Sixteenth Semiannual Report of the A.E.C. Pp. 137.

RME-3094. Annual Report for April 1, 1953 to March 31, 1954. J. W. GRUNER, ABRAHAM ROSENZWEIG, and D. K. SMITH, JR. Pp. 37. *Five short papers dealing with sedimentary and minerological problems of uranium ores in the Colorado Plateau.*

RME-3046. Annual Report for June 30, 1952 to April 1, 1953. PAUL F. KERR and others. Pp. 99; pl. 1; figs. 16. *Includes 7 short papers on hydrothermal alteration and uranium-bearing minerals in vicinity of Marysvale, Utah.*

RME-3095. Mineralogy of Uranium-Bearing Deposits in the Boulder Batholith, Montana. H. D. WRIGHT and others. Pp. 80; pls. 5; figs. 31.

RME-3096 (Pt. I). Annual Report for June 30, 1953 to April 1, 1954. PAUL F. KERR and others. Pp. 84; pls. 2; figs. 12. *Eight papers on uranium minerals from Marysvale district, Utah.* (Pt. II) Pp. 99; pls. 10; figs. 10. *Includes an X-ray line study of Uraninite by W. J. Croft; Progress report on the chemical environment of pitchblende by L. J. Miller and P. F. Kerr; and electron micrographs of synthetic pitchblende precipitates by F. P. Sciacca, Jr.*

AECU-2840. The Isotopic Composition and Distribution of Lead, Uranium, and Thorium in Pre-Cambrian Granite. G. R. TILTON and others. Pp. 27; figs. 2. *Age of zircon in granite from Monmouth township, Haliburton County, Ontario found to be 1050 million years.*

Statistical Yearbook 1954. Pp. 260. International Tin Study Group. Albani, The Hague, 1954. Price $7.70. *Deals exhaustively with all aspects of world tin*

industry. Gives International Tin Agreement; review of world tin industry; government regulations; tinplate and canning trades. For each country gives production, consumption, imports, exports, trade and tinplate canning industries.

Foraminifera, Their Classification and Economic Use, with an Illustrated Key to the Genera. JOSEPH A. CUSHMAN. Pp. 605; pls. 55. 4th Edit., 1948, 2nd Print., Harvard University Press, 1954. Price $12.50. *A much needed reprinting of this classical reference book on Foraminifera.*

The Orange Free State Gold Mines. PAUL KLEMPNER. Pp. 127. Supp. to 143a. Privately published, South Shields, Eng., 1954. Price 21 s. *Mining terms, taxation in S. Africa, uranium content, and general information on the mines of the Welkom, Odendaalsrus, and Virginia areas; statistical, financial, exploration and future prospects.*

Coals and Bitumens, and Related Fossil Carbonaceous Substances—Nomenclature and Classification. S. I. TOMKEIEFF. Pp. 122. Pergamon Press, Ltd., London, 1954. *Classification of carbonaceous substances: glossary of all terms used, with source reference; appendices on German, French and non-English terms, abbreviations, and synoptic tables; valuable reference.*

Bibliography of Geology Theses in Colleges and Universities of the United States. R. S. TURNER. Pp. 483. Petroleum Research Co., Denver, Colo., 1954. *A compilation of doctorate and masters theses by University, with author, title, degree, and date. It is preliminary because some data are still lacking on older titles, but that of Yale starts with 1867. A very valuable reference.*

The Bedrock Geology of the Woodbury Quadrangle. ROBERT M. GATES. Pp. 23; pls. 8; fig. 1. State Geological and Natural History Survey; Hartford, Conn. *Includes colored geologic map scale 1:31680.*

State Geol. Sur. of Kansas. Lawrence. 1954.

Bull. 109, Pt. 7. Electrical Resistivity Studies in the Kansas River Valley. D. F. MERRIAM. Pp. 97–112; pls. 2; figs. 5; tbls. 3.

Bull. 109, Pt. 8. Preliminary Spectrographic Investigation of Germanium in Kansas Coal. J. A. SCHLEICHER and W. W. HAMBLETON. Pp. 113–124; figs. 2; tbls. 2.

State Geol. Surv. of Illinois. Urbana. 1954.

Rept. of Invest. No. 175. Viscosity Studies of System CaO–MgO–Al_2O_3–SiO_2: IV, 60 and 65% SiO_2. J. S. MACHIN and TIN BOO YEE. Pp. 24; figs. 11; tbls. 2.

Circ. 191. Filter Cake Formation and Water Losses in Deep Drilling Muds. WOLF VON ENGELHARDT. Pp. 24; figs. 12; tbls. 6.

Forty-Second Annual Report by the State Inspector of Mines for the Year Ending June 30, 1954. Office of the State Inspector of Mines, Albuquerque, N. M. Pp. 56.

Mineral Resources of Fort Defiance and Tohatchi Quadrangles, Arizona and New Mexico. J. E. ALLEN and ROBERT BALK. Pp. 192; pls. 16; figs. 21; tbls. 19. State Bur. of Mines and Mineral Res. Bull. 36, N. M. Inst. of Mining and Technology, Socorro, N. M. *Detailed geologic study; describes known mineral resources, stratigraphy, structure, and geomorphology. Includes colored geologic map 22" × 36", scale 1:48,000 on photo-mosaic base.*

New York Dept. of Conserv. Albany. 1953.

Bull. GW-32. Ground Water in Bronx, N. Y., and Richmond Counties with Summary Data on Kings and Queens Counties, N. Y. City, N. Y. N. M. PERLMUTTER and THEODORE ARNOW. Pp. 86; pls. 5; figs. 11; tbls. 7.

Bull. GW-33. The Ground-Water Resources of Washington County, N. Y. R. V. CUSHMAN. Pp. 65; pls. 3; figs. 10; tbls. 10.

Magnetic Anomalies of the Santa Clara, N. Y., Quadrangle. B. M. SHAUB. Pp. 28; pls. 12; figs. 3; tbls. 2. Rept. of Inv. No. 4, N. Y. State Science Serv., Albany. 1954.

North Dakota Geol. Surv., Grand Forks. 1954.

Twenty-Eighth Biennial Rept. of the Geol. Sur. W. M. LAIRD. Pp. 19.
Circulars, Nos. 87–92. *Summary of following wells: Swanson No. 1; Harold Billey No. 1; Sarah Dunbar No. 1; Clarence and M. Jacobs F14-24-P; Sioux Tribal No. 1; Charles Dvorak No. F42-6-P.*

Geology of Coshocton County. R. E. LAMBORN. Pp. 245; pl. 1; figs. 5.

Div. of Geol. Sur., Columbus, Ohio. 1954. *Detailed physiography, stratigraphy and economic geology of area including coal, gas and oil. Geol. map 22" × 31", scale 1:62,500.*

Rept. of the State Dept. of Geology and Mineral Industries. M. L. BINGHAM, NIEL ALLEN and AUSTIN DUNN. Pp. 30. Bull. 45. Dept. of Geology and Mineral Industries, Portland, Oregon. 1954.

Silica Sand Resources of Western Va. W. D. LOWRY. Pp. 62; pls. 6; figs. 24; tbls. 35. Bull. of the Va. Polytech. Inst. Eng. Expt. Ser. No. 96. Va. Polytech. Inst. 1954. Price 75 cts. *Includes geology of silica sand deposits and description of individual deposits.*

Engineering Geology Reference List. Committee on Teaching Aids. Pp. 92. Geol. Soc. of America. 1954. *Preliminary listing of references to geologic papers on engineering problems.*

Geol. Soc. of America. 1953, 1954.

Bibliography and Index of Lit. of Uranium and Theorium and Radioactive Occurrences in the U. S. Part 2: Calif., Idaho, Mont., Oreg., Wash. and Wyo. Pp. 1103–1172. **Part 3: Colo. and Utah.** Pp. 467–590. MARGARET COOPER. *Separates available from the Geol. Soc. of America, price 25 cts. and 50 cts. respectively.*

Memoir 62. Ordovician Cephalopod Fauna of Baffin Island. A. K. MILLER, WALTER YOUNGQUIST and CHARLES COLLINSON. Pp. 234; pls. 63; figs. 20; tbls. 2.

Practical Refractometry by Means of the Microscope. R. M. ALLAN. Pp. 63; figs. 10. Cargille Lab., Inc., New York, N. Y. 1954. Price $1.00.

Quebec Dept. of Mines, 1954.

Rept. 61. Parts of Hebecourt, Duparquet and Destor Townships. R. B. GRAHAM. Pp. 64; pls. 9; figs. 8. *General geology and economic geology of area. Four colored geologic maps, 28" × 26", and one, 14" × 26", scale 1:12,000.*

Rept. 62. The Tourelle and Courcelette Areas, Gaspe Peninsula. H. W. MCGERRIGLE. Pp. 63; pls. 16. *General geology; includes two colored geologic maps, scale 1:63,360.*

Ontario Dept. of Mines, Toronto. 1953.

Sixty-Second Annual Rept. Part 1. Pp. 97. *Statistical review of mineral industry for 1952, mining accidents in 1952.* **Part 4. Geology of the Mamainse Point Copper Area.** J. E. THOMSON. Pp. 25; pls. 12. *General geology of area. Colored geologic map, scale 1"–1,000.* **Part 7. Geology of the North Half of Holloway Township.** J. SATTERLY. Pp. 38; pls. 17. *General geology. Colored geologic map, scale 1"–1,000.*

Geologia de Fronteras. T. G. CASTELLANOS. Pp. 39; figs. 13. Argentina, 1954. *Discussion of the effect of geologic processes on international boundaries.*

Dept. of Natl. Dev., Melbourne, 1954.

Vol. 7. No. 1. The Australian Mineral Industry. Pp. 43; figs. 5; tbls. 9. Price 3/–. *Beginning with this issue to be published quarterly in two parts: Part 1—Quarterly Review, reviews current happenings in mineral industry and Part 2—Quarterly Statistics, states statistics of mineral industry.*

1953 Review. The Australian Mineral Industry. Pp. 201. Price 12/–. *Includes general review, review of metals and minerals and general summary of states.*

Annales du Service des Mines et du Service Géographique et Géologique. Pp. 111; pls. 4; figs. 42. Comité Spécial du Katanga, Bruxelles, 1954. *Includes following papers: La nappe phréatique des environs d'Elisabethville et les phénomènes connexes d'altération superficielle. A. Beugnies. Le site hydrogéologique des sources de la Kimilolo. R. Rorive. Note sur le découverte de récifs algaires dans l'assise du calcaire de kakoniwe à Gombela (Katanga). A. Beugnies et P. Dumont. L'aerolithe de Kalaba (Katanga). A. Beugnies et R. Rorive. Observations géologiques le long du 24e méridien entre les parallèles 8° et 9° 30" sud. G. Ninove.*

The Economic Geology of the Fife Coalfields, Area III, Markinch, Dysart and Leven. J. KNOX. Pp. 134; pls. 5; figs. 36. Dept. of Sci. and Indus. Res., Edinburgh, 1954. Price 12s 6d. *Detailed description of stratigraphy and structure.*

Acta Geologica, Academiae Scientiarum, Hungaricae. SZADECZKY-KARDOSS E. Pp. 190. Tomus II, Fasciculi 1–2. Acta Geologica, Budapest, 1953. *Fourteen papers of general interest in German, French, English, or Russian.*

The Quarterly Journal of the Geological, Mining and Metallurgical Society of India. Vol. XXIV, No. 1–4, 1952. Pp. 220. *A well-illustrated and very interesting Silver Jubilee Volume containing a chapter on the Society's activities in the present development of India; a review of past activities; life sketches of past presidents of the Society and summaries of their addresses to the Society; and 27 papers on geologic, mining, and metallurgical subjects.*

Le "Argille Brecciate" Siciliane. LEO OGNIBEN. Pp. 92; pls. 5; figs. 36. Società Cooperativa Tipografica, Dadova, 1954.

Geological Survey of Japan, Hisamoto-cho, Kawasaki-shi, 1954.

Rept. No. 161. Natural Gas in the Vicinity of Yamagata City. KOJI MOTOJIMA and YOSHIJIRO SHINADA. Pp. 72; pls. 3; figs. 54; tbl. 1. *Geochemical study of ground water to determine natural gas composition and reserves. Japanese text.*

Explanatory Text of the Geological Map of Japan. Kami-Ashibetsu (Sapporo-6). I. SHIMIZU, K. TANAKA and I. IMAI. Pp. 100; pls. 7; figs. 6; tbls. 5. **Niki (Sapporo-19).** R. OTA, F. UEMURA. Pp. 65; figs. 3. **Otaru-Seibu (Sapporo-10).** S. IGI and T. KAKIMI. Pp. 28; pls. 2; figs. 4; tbls. 2. **Rumoi (Asahigawa-41).** K. TSUSHIMA and S. YAMAGUCHI. Pp. 24; tbl. 1. **Tokushumbetsu (Sapporo-51).** RYOHEI OHTA. Pp. 60; figs. 5. **Tomamae (Asahigawa-33).** K. TSUSHIMA, K. MATSUNO, and S. YAMAGUCHI. Pp. 22; figs. 2; tbls. 2. *Each includes colored geologic map, scale 1:50,000, Japanese summary of geology, and English abstract.* **Kagoshima. Sheet 15. (Geologic Map of Japan.)** *Colored geologic map, scale 1:500,000.*

The Geology of the Country between Concession and Msonneddi (Mazoe District). J. G. STAGMAN. Pp. 47; pls. 6; tbls. 5. Southern Rhodesia Geol.

Survey Bull. No. 41, Salisbury, 1953. *General geology and economic geology of area. Includes colored geologic map, scale 1:50,000.*

Consejo Superior de Investigaciones Cientificas, Barcelona, Spain.

Vol. 1, No. 2, 1954. Publicaciones del Departamento de Cristalografia y Mineralogia. Pp. 61–109. *Includes papers on crystallography of cis-triphenylterpine and cyanacetylhydracide, description of roselite deposits in Morocco, estimation of transmission factors of crystals for X-ray diffraction, and study of cleavage and slip planes in crystals.*

Vol. 1, No. 1, 1953. Publicaciones del Departamento de Cristalografia y Mineralogia. Pp. 59. *Includes papers on solubility of conic crystals, crystal structure isonictinic acid hydracide and 3 papers on use and design of new X-ray camera to be used with flat specimens.*

A Study of the Metamorphic Rocks of Karema and Kungwe Bay, Western Tanganyika. J. SUTTON, J. WATSON, and T. C. JAMES. Pp. 70; pls. 2; figs. 15; tbls. 6. Bull. 22. Tanganyika Geol. Survey Dept., 1954. Price Shs. 12/50. *Includes 2 colored geologic maps, Karema area, scale 1:7,500 and Mgambo-Katumbi area, scale 1:25,000.*

Union of South Africa Dept. of Mines, Pretoria, 1953.

Coal Survey Memoir 2. The Northern Natal Coal-Field (Area No. 2) The Utrecht–Newcastle Area. Part 1. Geological. J. J. G. BLIGNAUT and F. J. J. FURTER. **Part 2, Chemical and Physical.** W. H. D. SAVAGE. Pp. 228; pls. 3; figs. 32. Price 30s. *Includes general geology, structure of area, description of coal bearing areas and chemical and physical characteristics of coal. Includes colored geologic map, scale 1:125,000 and geologic map in 2 sheets, scale 1:50,000.*

The Geology of the Koedoestrand Area, Northern Transvaal. An Explanation of Sheets 35 and 36 (Koedoestrand). H. N. VISSER. Pp. 110; pls. 14; figs. 3. Price 10s. *General geology and economic geology of area. Includes colored geologic map, scale 1:125,000.*

Ministerio de Minas e Hidrocarburos, Venezuela, 1954.

Ano V, No. 14. Revista de Hidrocarburos y Minas. Pp. 350. *Contains reviews of petroleum and mining industry for 1953. Well-illustrated with many tables, diagrams and photographs.*

Ano V, No. 15. Revista de Hidrocarburos y Minas. Pp. 142. *Includes article by C. Montoza relating experiences on several botanical trips in eastern Venezuela through gold and diamond areas. Illustrated by 5 sketch maps and 29 photographs, 8 of which are in full color.*

SCIENTIFIC NOTES AND NEWS

WILLIAM W. TAMPLIN arrived recently in Djakarta, Indonesia. He is scheduled to remain there with the J. G. White Engineering Corp., which serves the Indonesian Government as consultants, until the end of 1955. Mr. Tamplin will be concerned principally with the exploration and development of mineral resources.

H. I. ALTSHULER, cosulting mining engineer, is in Brazil for a year-end inspection of the operations of the St. John d'el Rey Mining Co. Ltd.

A. K. SNELGROVE, who has been lecturing at the University of Hong Kong on a Fulbright award, has returned to Houghton, Mich., where he is head of the dept. of geological engineering, Michigan College of Mining & Technology.

GERALD M. FRIEDMAN has resigned as assistant professor of geology, University of Cincinnati, to be a consulting geologist with Harico Mining & Development Co. and Talvey Metal Mines, Sault Ste. Marie, Ont.

E. S. WILLBOURN, Deputy-Director of Colonial Geological Surveys, London, and W. J. FELTON, Secretary of the Institution of Mining and Metallurgy, London, were appointed to be Officers of the British Empire in the New Year's Honours List.

The Senate-House Committee on Defense Production has reported that the government has achieved its goals on 30 of the 75 materials being acquired under the stockpiling program. Only 18 materials, it says, are now less than 50 percent of the established targets.

MACK C. LAKE, 64, former president of United States Steel Corporation's Orinoco Mining Company, died in San Francisco, California on November 10. The internationally known mining engineer and geologist had directed explorations that led to the discovery of the iron ore deposits at Cerro Bolivar, Venezuela, seven years ago. He had retired from the presidency of Orinoco last year.

EARL M. IRVING, chief of the United States Geological Survey in the Philippine Islands, has returned to the United States on vacation.

FRANK AYER, former general manager of Mufulira Copper Mines Ltd. and Roan Antelope Copper Mines, Ltd., Northern Rhodesia, recently returned to the operations for a visit after a 14-year absence.

WILLARD BENHAM, mining engineer, is now at the San Alberto tungsten mine, in charge of exploration activities. The mine is under option to the San Luis Mining Company, Tayoltita, Durango, Mexico.

DR. PHILLIP L. MERRITT has been appointed senior geologist for E. J. Longyear Co. Dr. Merritt will initiate consulting services in New York City. He was formerly the assistant director for exploration for the Atomic Energy Commission.

BURT HARTMANN, R. A. HILDEBRAND, R. T. BROWN, and ROBERT HURST, graduate geological and mining engineers of the Colorado School of Mines, have

formed Technical Services, Inc., a geological service organization, at Grand Junction, Colo.

H. W. MALLERY, former geologist with New Jersey Zinc, is now in Bonne Terre, Mo., serving as geologist for the St. Joseph Lead Co.

H. DEWITT SMITH, of Newmont Mining Corp., was installed as president of the AIME for 1955 at the Chicago meeting, succeeding LEO J. REINARTZ.

ALLEN JAMES is geologist for Kennecott Copper in the Utah Copper division.

DAVID WHITE has joined Alcoa Mining Co. at Bauxite, Ark. He is succeeded as field geologist, Oregon department of geology, by MAX SCHAFER, formerly of USGS.

MITCHELL A. LIGHT is now research geologist with California Research Corp., La Habra, Calif. He was formerly assistant professor in the geology department of the University of Massachusetts, Amherst.

REPUBLIC STEEL CORP., Cleveland, has proved up a minimum of 25-million metric tons of rich rutile ore on its 7-mile long by 1½-mile wide 38 adjoining claims in the state of Oaxaca, Mexico.

MERLE H. GUISE, consulting geologist, is now engaged in scouting for uranium, rare earths, and tantalite-columbite deposits in southern California.

H. R. COOKE, JR., formerly with the Northern Peru Mining and Smelting Company in Lima, Peru, has accepted a position as geologist with Martin, Sykes, Woods & Associates in Caracas, Venezuela.

MOHAMED DAMIH ALLA, geologist for the Egyptian Department of Mines, is on a six-month tour of the Federation of Rhodesia and Nyasaland.

WILLIAM B. HEROY is a director of the Diamond Oil Well Drilling Company of Midland, Texas. He is president of the Geotechnical Corporation.

D. DALE CONDIT, of Greenwich, Connecticut, has returned from a tour of 6 weeks in British Somaliland and neighboring parts of northeastern Africa.

W. C. KRUMBEIN has been granted a leave of absence from Northwestern University to study statistical methods in geology. He will spend several months as guest worker on problems of statistical design at the National Bureau of Standards in Washington, D. C., and about two months at Princeton University as Research Associate in the Department of Mathematics and Visiting Fellow of the Geology Department.

HUGH D. MISER was congratulated on his 70th birthday, December 18, 1954, by the presentation of a bound volume of more than 300 letters from friends, illustrated with photographs and drawings, commemorating associations and incidents of past years. He has been with the United States Geological Survey since 1907.

RICHARD M. FOOSE, Chairman of the Department of Geology, Franklin and Marshall College, has received a $10,000 grant from the National Science Foundation for geologic studies in the Beartooth Mountains of Wyoming and Montana. He will be engaged in mapping portions of the perimeter of the Beartooth Mountains in an attempt to determine the history of the mountain deformation.

The Society of Exploration Geophysicists will hold its tenth annual Gulf Coast meeting May 19 and 20, 1955 in San Antonio, Texas, where two full days of technical sessions devoted to the latest developments in exploration for oil and other minerals will be held. About 1,000 earth scientists are expected to attend.

The first nine Gulf Coast meetings of SEG were sponsored by the society's Houston section. This year the Southeastern Geophysical Society of New Orleans and the Geophysical Society of South Texas in San Antonio will serve as joint sponsors with the Houston section. As a result, Narvarte said, the area served by the convention has been broadened and papers on oil exploration will be of wider interest.

Co-chairman of the meeting is W. L. Crawford, Petty Geophysical Engineering Co., San Antonio, and chairmen of the convention committees are: J. O. Parr, Petty Geophysical Engineering Co., program; Dr. John C. Cook, Southwest Research Institute, registration; A. F. Hasbrook, Petty Geophysical Engineering Co., arrangements; W. R. Gray, Monterrey Exploration Co., housing; W. B. Lee, Gulf Oil Corp., Houston, finance; Van A. Petty, Jr., Petty Geophysical Engineering Co., entertainment; Thomas S. West, West & Gill, publicity; and M. G. Frey, the California Co., New Orleans, program publication.

FELIX CHAYES of the Carnegie Institution of Washington and WILLIAM W. RUBEY of the U. S. Geological Survey have been appointed for this term as visiting professors in the Division of the Geological Sciences at the California Institute of Technology.

Dr. Chayes, appointed visiting professor of petrology for the winter term, is petrologist in the Geophysical Laboratory of the Carnegie Institution. A graduate of New York University, he received M.A. and Ph.D. degrees from Columbia University. Before joining the Carnegie Institution, he served as a chemist-petrographer in the U. S. Bureau of Mines and as a mineralogist at the Massachusetts Institute of Technology.

Professor Rubey will arrive March 1 on a sixth-month appointment as visiting professor of geology. An alumnus of Missouri, Yale, and Johns Hopkins Universities, he has been associated with the U. S. Geological Survey since 1924 and Survey research geologist since 1947. He is a member of the National Academy of Sciences, a past president of the Geological Society of America, and since 1952 has served as chairman of the Division of Geology and Geography of the National Research Council. He is well known for his work on fluid mechanics as applied to geological processes of running water, deposition, and sedimentation, and for his studies of the origin and evolution of the oceans through geologic history.

F. J. PETTIJOHN, professor of geology, The Johns Hopkins University, Baltimore, Maryland, became president of the Society of Economic Paleontologists and Mineralogists on March 31. Serving with Pettijohn on the 1955–56 Council will be HANS THALMANN, Stanford University, as first vice-president; HAROLD N. FISK, Humble Oil and Refining Company, Houston, Texas, as second past-president, and two other newly elected officers: vice-president ROBERT R. SHROCK, professor of geology, Massachusetts Institute of Technology, Cambridge; and secretary-treasurer SAMUEL P. ELLISON, JR., professor of geology, University of Texas, Austin. Appointed editors of the Society's two publications are: A. K. MILLER, professor of geology, and W. M. FURNISH, associate professor of geology, University of Iowa, Iowa City (co-editors of the *Journal of Paleontology*); JACK L. HOUGH and RALPH E. GRIM, both of the University of Illinois, Urbana (editor and acting editor respectively of the *Journal of Sedimentary Petrology*).

CARL TOLMAN, vice-chancellor and dean of faculties at Washington University, has been elected vice-president and chairman of the geology and geography section of the American Association for the Advancement of Science.